Hadron Polarimetry Today
and
Improvements for EIC

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Inaugural Meeting of the EIC Polarimeter WG

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BROOKHAVEN NATIONAL LABORATORY

"Configuration Manual Polarized Proton Collider at RHIC." I. Alekseev et al. (2004)

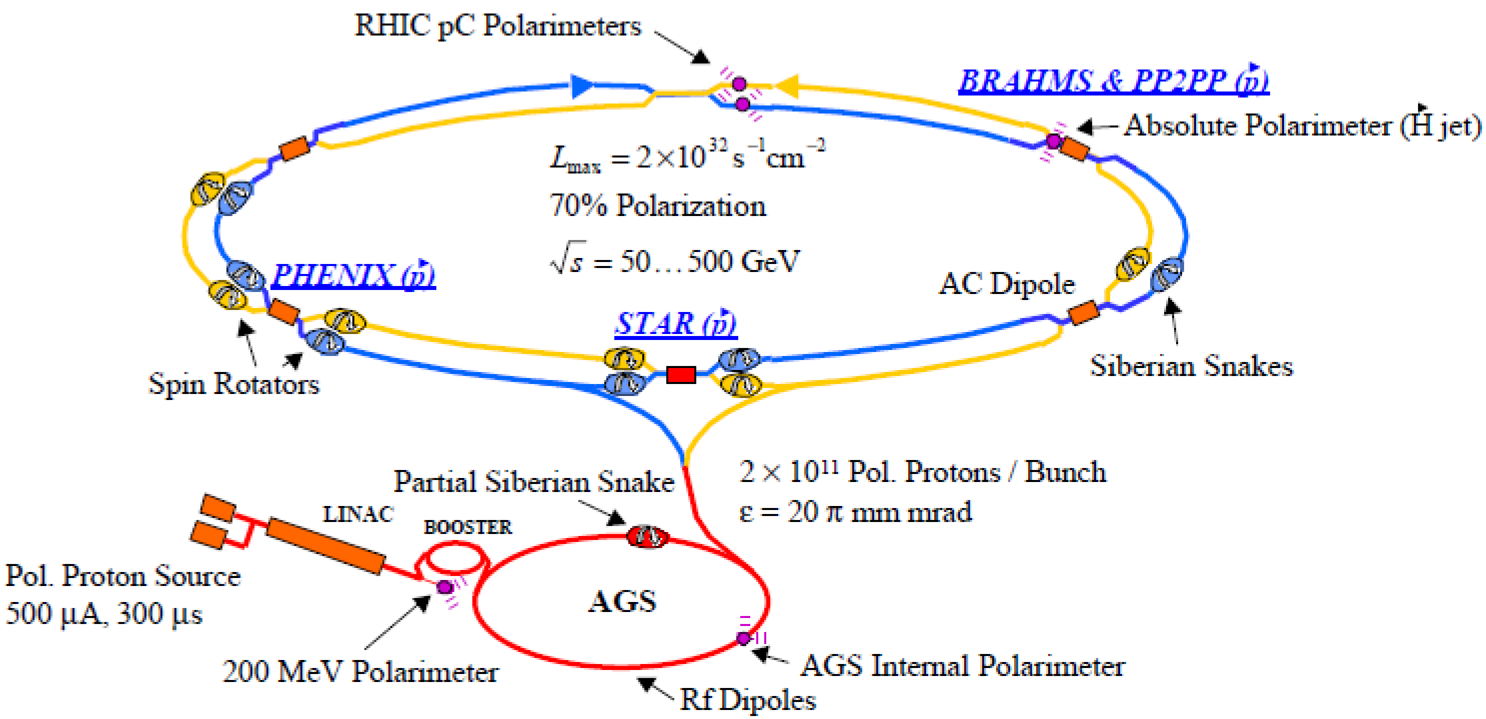
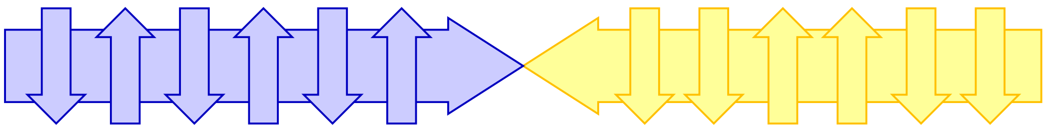
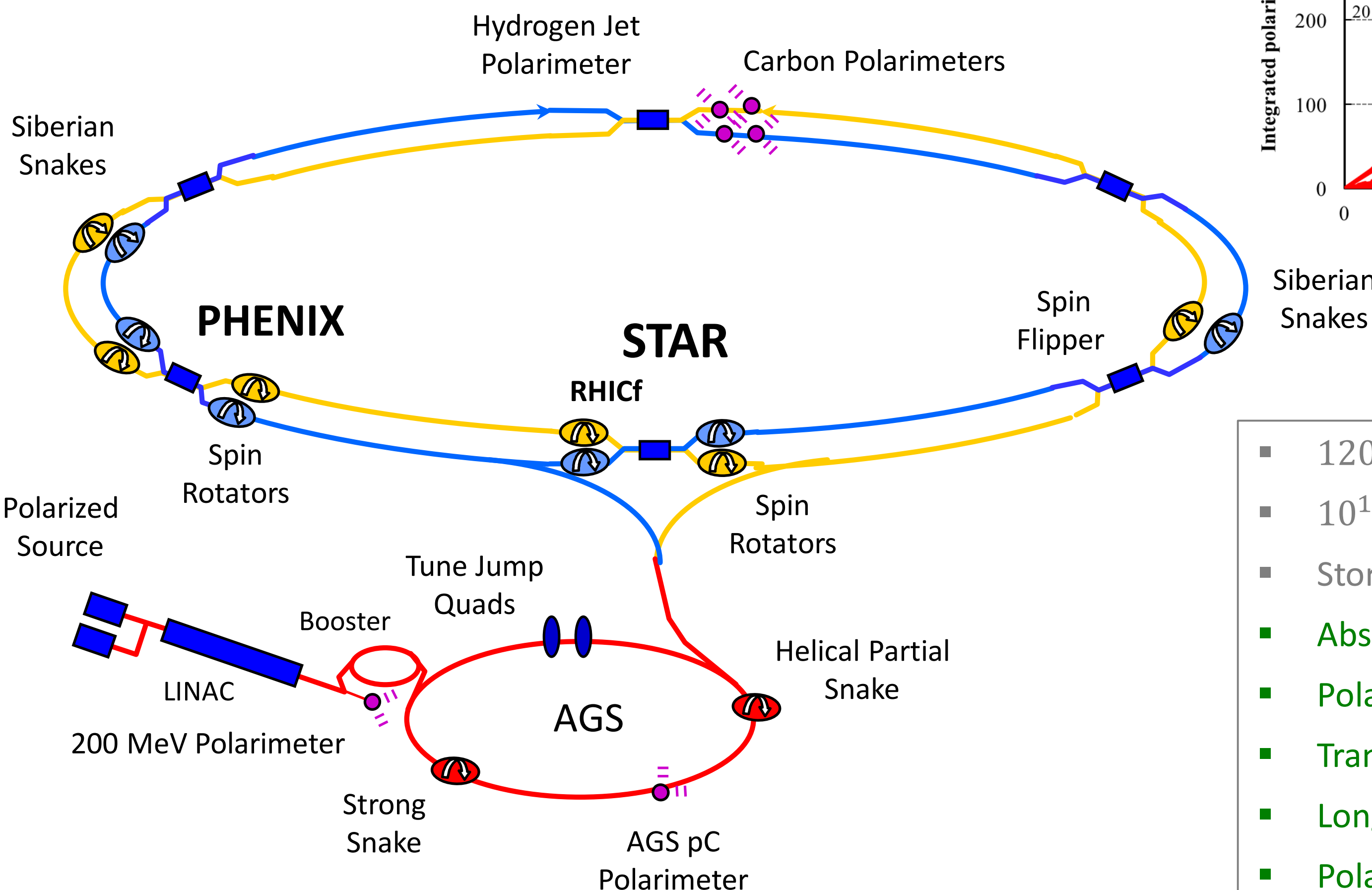
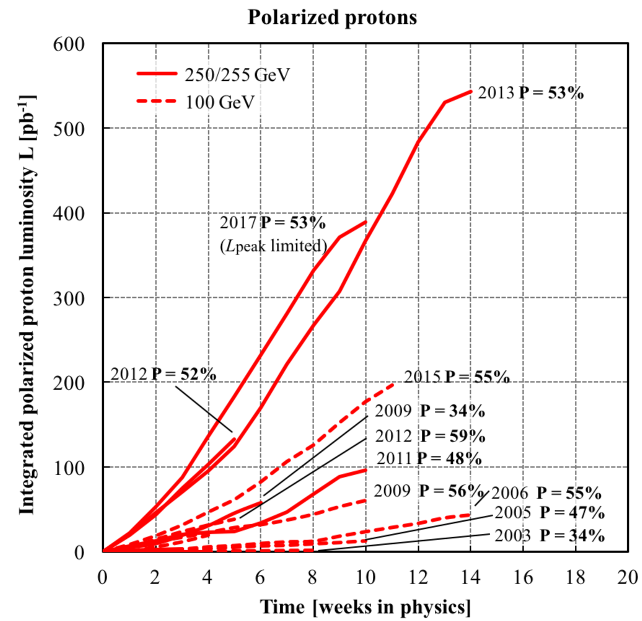


Figure 1.1: The Brookhaven hadron facility complex, which includes the AGS Booster, the AGS, and RHIC. The RHIC spin project will install two snakes per ring with four spin rotators per detector for achieving helicity-spin experiments.

Polarized Protons in RHIC

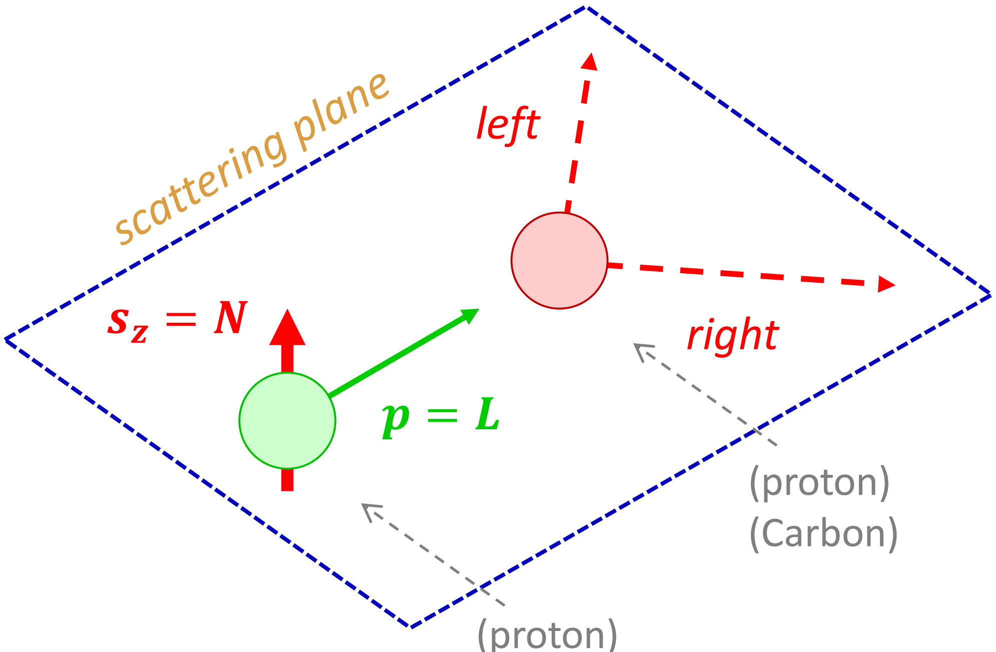






- 120 bunches (106 ns spacing)
- 10^{11} protons per bunch
- Store ≈ 8 hours
- Absolute beam polarization
- Polarization decay in store
- Transverse polarization profile
- Longitudinal polarization profile
- Polarization vector in experiment

Elastic Proton-Proton Scattering



$$A_N = \frac{d\sigma_{left} - d\sigma_{right}}{d\sigma_{left} + d\sigma_{right}}$$

$$\varepsilon = A_N \cdot P = \frac{N_L - N_R}{N_L + N_R}$$

(*) perpendicular to polarization vector

$$\varphi(s,t) = \langle \lambda_C \lambda_D | \varphi | \lambda_A \lambda_B \rangle$$

$$\varphi_1(s,t) = \left\langle +\tfrac{1}{2} + \tfrac{1}{2} \middle| \varphi \middle| + \tfrac{1}{2} + \tfrac{1}{2} \right\rangle$$

$$\varphi_2(s,t) = \left\langle +\tfrac{1}{2} + \tfrac{1}{2} \middle| \varphi \middle| - \tfrac{1}{2} - \tfrac{1}{2} \right\rangle$$

$$\varphi_3(s,t) = \left\langle +\tfrac{1}{2} - \tfrac{1}{2} \middle| \varphi \middle| + \tfrac{1}{2} - \tfrac{1}{2} \right\rangle$$

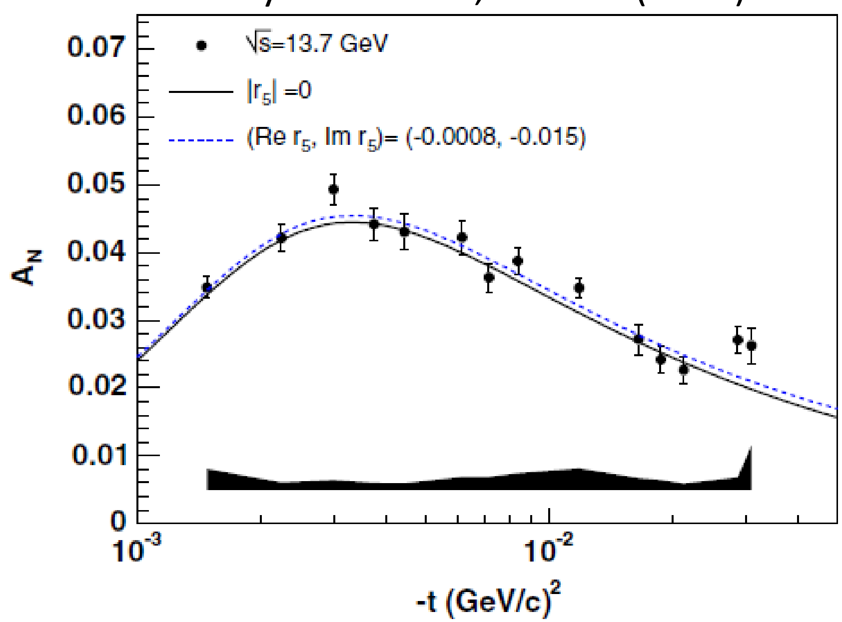
$$\varphi_4(s,t) = \left\langle +\tfrac{1}{2} - \tfrac{1}{2} \middle| \varphi \middle| - \tfrac{1}{2} + \tfrac{1}{2} \right\rangle$$

$$\varphi_5(s,t) = \left\langle +\tfrac{1}{2} + \tfrac{1}{2} \middle| \varphi \middle| + \tfrac{1}{2} - \tfrac{1}{2} \right\rangle$$

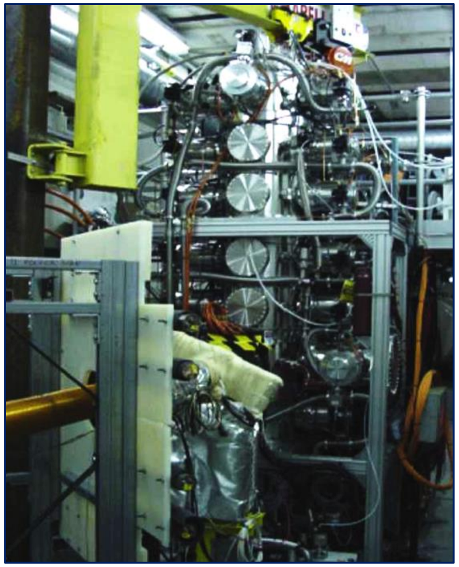
$$A_N \frac{ds}{dt} = -\frac{4\pi}{s^2} \mathrm{Im}\left[\varphi_5^{em*}(s,t)\varphi_+^{had}(s,t) + \varphi_5^{had*}(s,t)\varphi_+^{em}(s,t)\right]$$

no-flip amplitude: $\varphi_+(s,t) = \frac{1}{2}[\varphi_1(s,t) + \varphi_3(s,t)]$

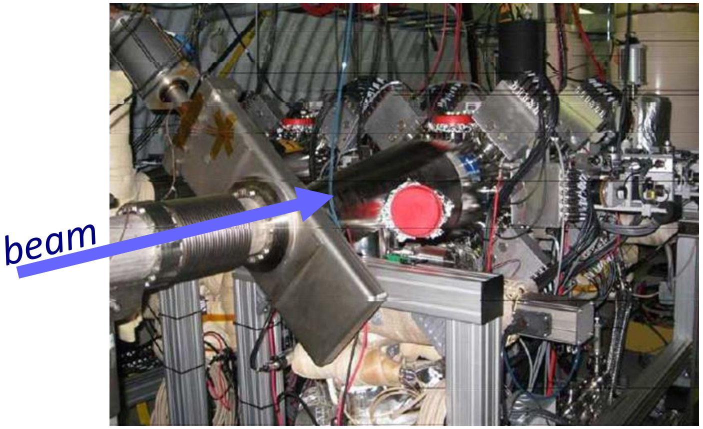
Phys. Rev. D 79, 094014 (2009)



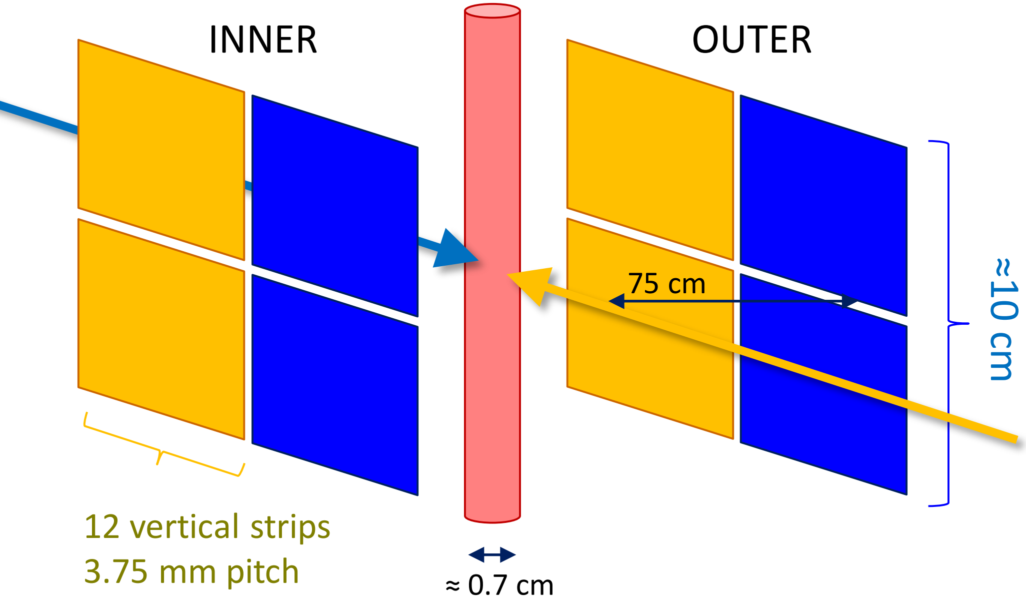
Polarimeter Setup

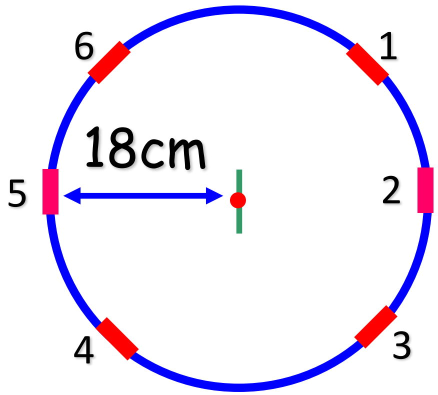


- Atomic hydrogen jet target (polarized)
- Set of eight Hamamatsu Si strip detectors
- 12 strips
  - 3.75 mm pitch
  - 500 μm thick
- Uniform dead layer ≈ 1.5 μm

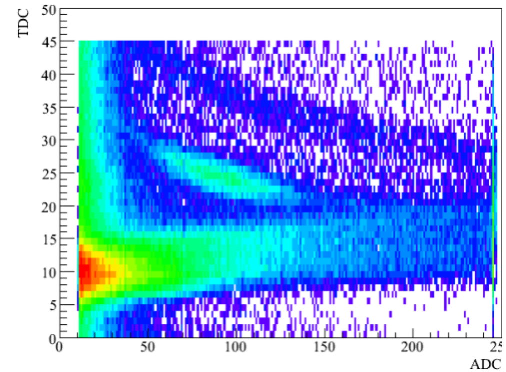


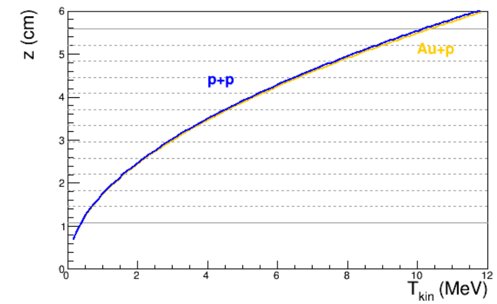
- Ultra thin Carbon ribbon target
- $5\ \mathrm{mg/cm^2}$
- Different detector coverage and targets (horizontal, vertical)
- Two per RHIC ring

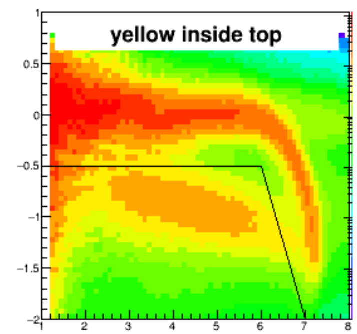




- Reconstruction
  - Energy calibration (→ slide 19)
  - Time of flight adjustment (→ slide 27)
  - Geometry alignment (→ slide 26)
- Signal selection
  - Remove punch through hits (→ slide 28)
  - Missing mass $|m_{miss} - m_p| < 50\ \mathrm{MeV}/c^2$
  - Time of flight $|\Delta t| < 5\ \mathrm{ns}$
- Asymmetry calculation
  - Inclusive and signal bunches
  - Background asymmetry correction





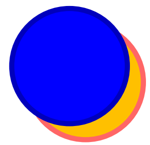


$$\epsilon_S = \frac{\epsilon_I - r\epsilon_B}{1 - r}$$

$$r = \frac{B}{S + B}$$

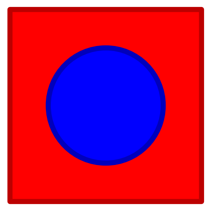
Luminosity Weighted Polarization

Experiments



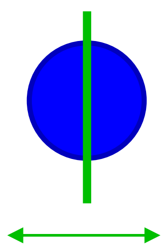
$$P = \frac{\int P(x,y,t) \cdot I_B(x,y,t) \cdot I_Y(x,y,t)dxdydt}{\int I_B(x,y,t) \cdot I_Y(x,y,t)dxdydt}$$

HJET Polarimeter



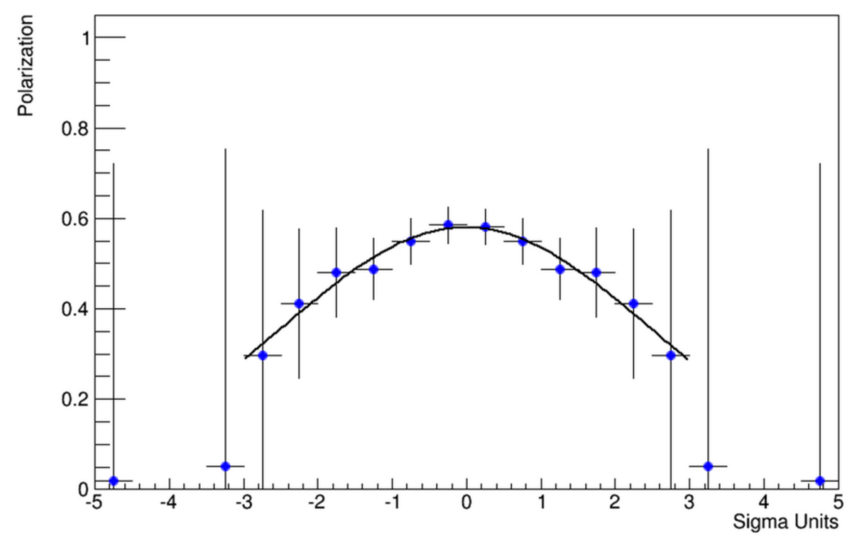
$$P = \frac{\int P(x,y,t) \cdot I(x,y,t)dxdydt}{\int I(x,y,t)dxdydt}$$

Carbon Polarimeter



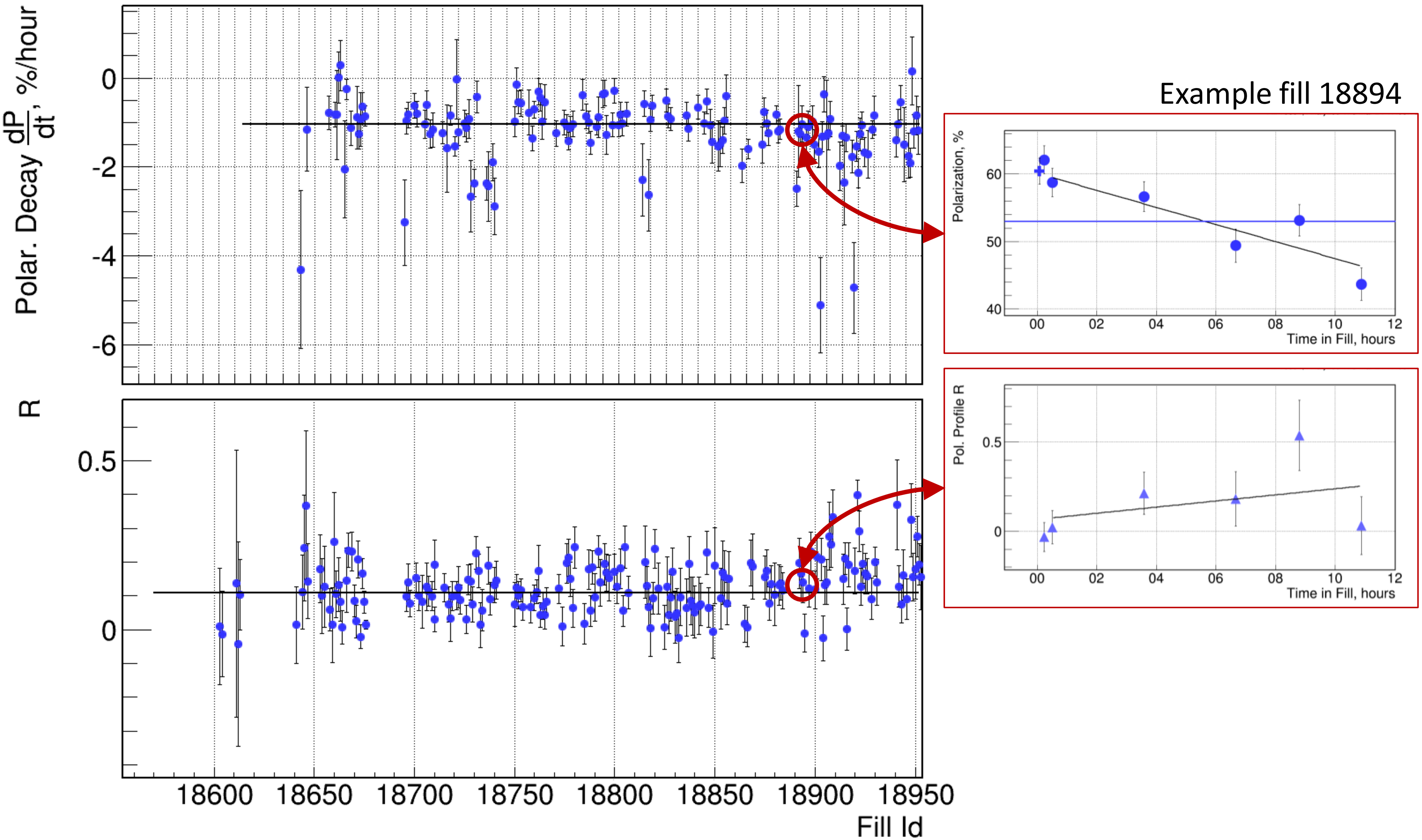
sweep

$$P = P_{max} \cdot \left(\frac{I}{I_{max}}\right)^R$$



beam width

Polarization Decay & Profile



2015 RHIC run

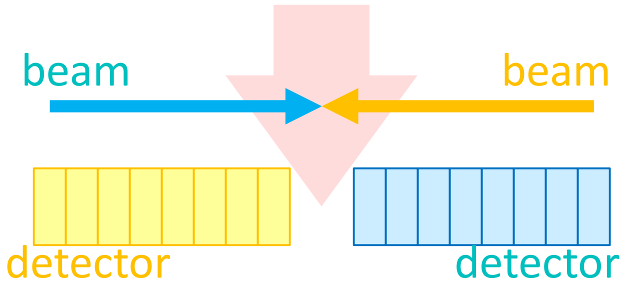
→ https://www.phy.bnl.gov/cnipol/

Asymmetries in HJET

$$P_{Beam} = -\frac{\varepsilon_{Beam}}{\varepsilon_{Target}} P_{Target}$$

from Breit-Rabi measurement

$$\boxed{\varepsilon = A_N \cdot P}$$



1

Polarization independent background

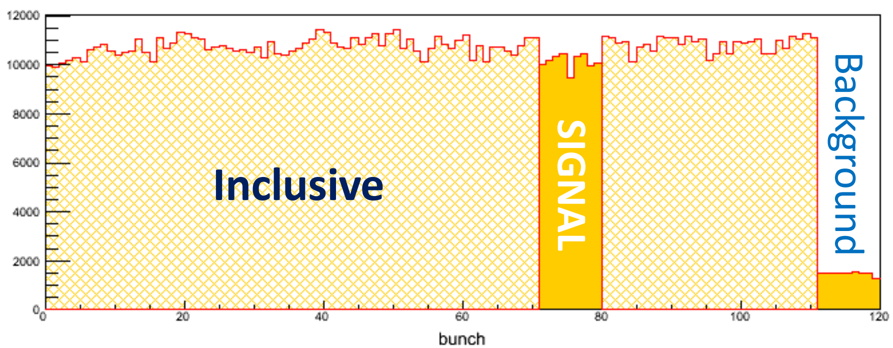
$$\varepsilon = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow} + 2 \cdot N_{bg}} \Rightarrow \frac{\varepsilon_B}{\varepsilon_T} = \frac{N_B^{\uparrow} - N_B^{\downarrow}}{N_T^{\uparrow} - N_T^{\downarrow}}$$

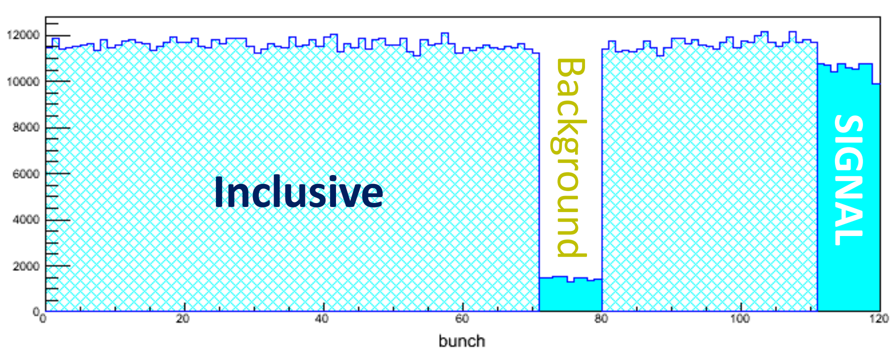
2

Polarization dependent background

$$\varepsilon = \frac{\varepsilon_{inc} - r \cdot \varepsilon_{bg}}{1 - r}$$

background fraction $r = N_{bg}/N$





Signal & Background

- Inclusive (normalized to peak)

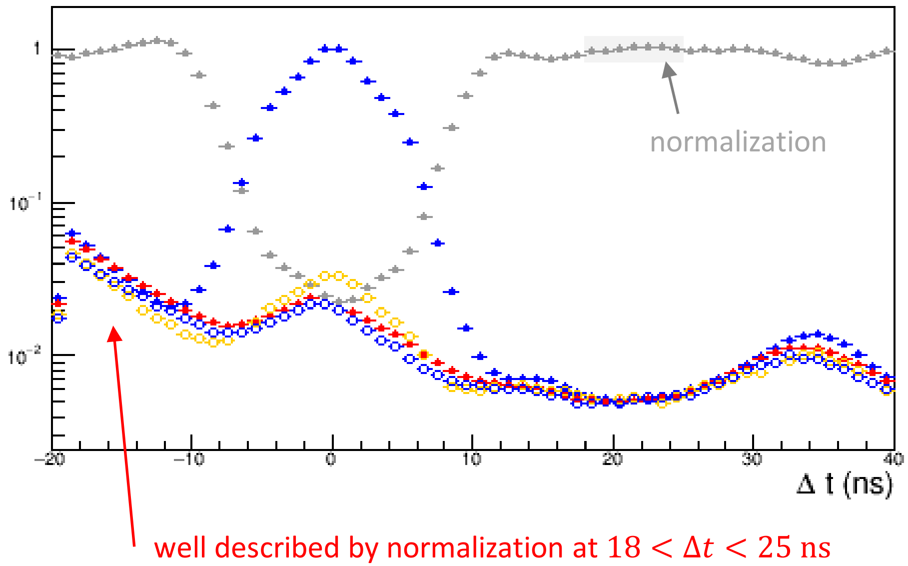
$$|m_{miss} - m_p| < 50 \text{ MeV}/c^2$$

- Background (normalized to signal at $18 < \Delta t < 25$ ns)

$$|m_{miss} - m_p| > 120 \text{ MeV}/c^2$$

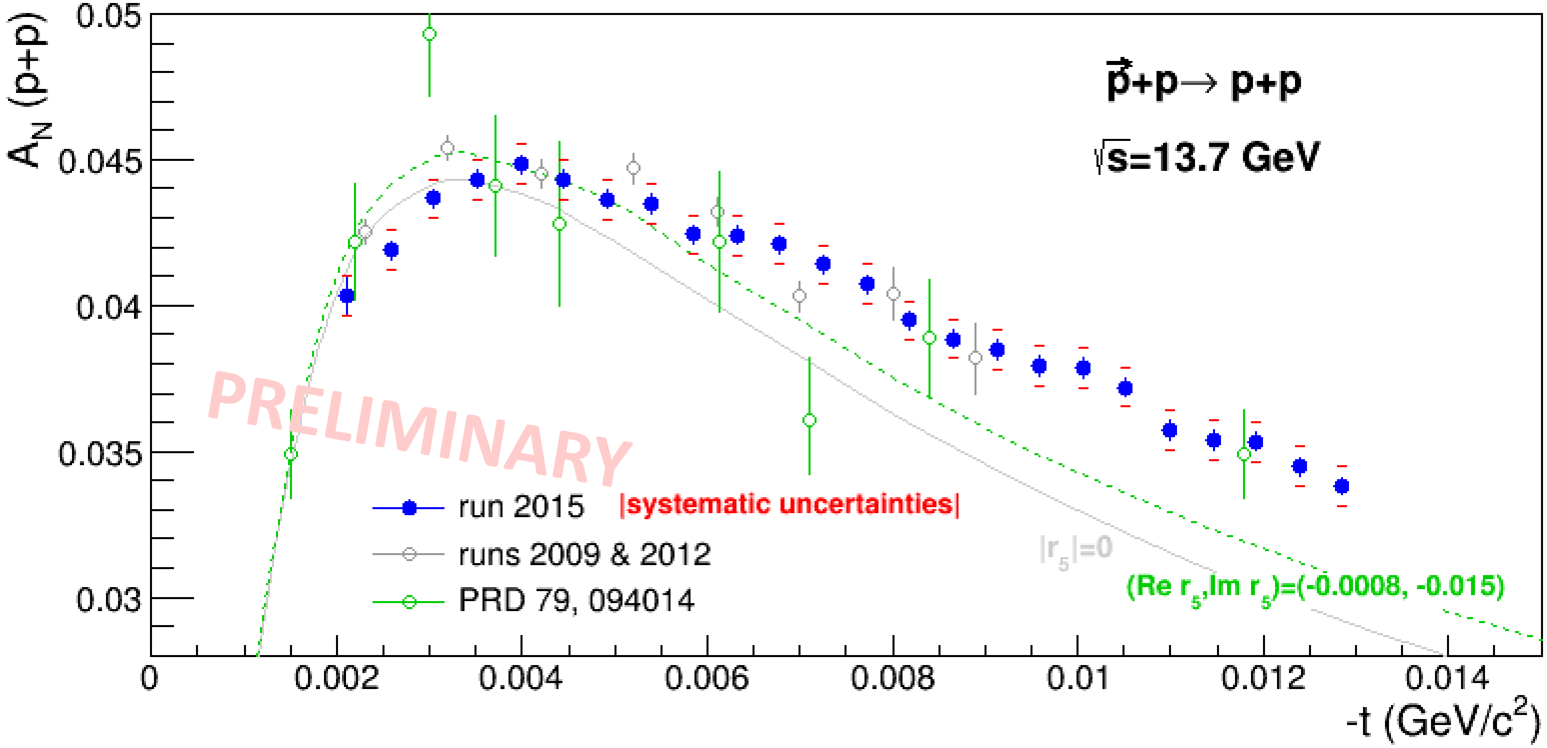
- Background fraction
  - Background in yellow abort gap (should be clean blue signal)
  - Signal in blue abort gap (should be only background from yellow beam)

Example (blue beam, $2 < E_{kin} < 3$ MeV)



	$m_{miss} \approx m_p$	$m_{miss} \neq m_p$
Inclusive	●	○
Abort gap	○	
Signal		●

Analyzing Power: $A_N(\vec{p} + p)$



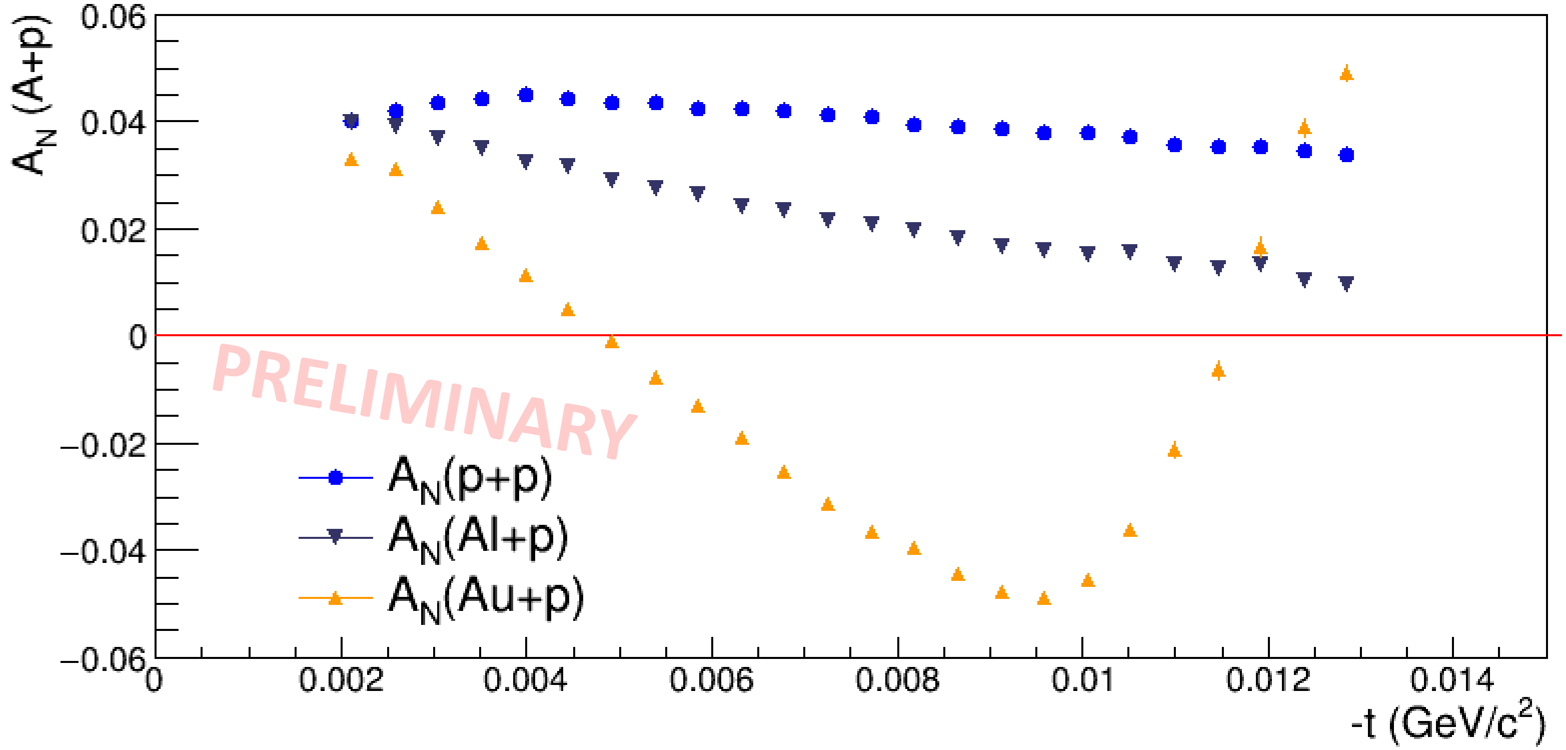
Atomic hydrogen target polarization $P = 96\%$

Molecular component $R_{H_2} = 3\%$ (by mass)

Global uncertainty from target polarization not included

$-t$-range can be extended with punch-through protons

Analyzing Power: $A_N(\vec{p} + A)$



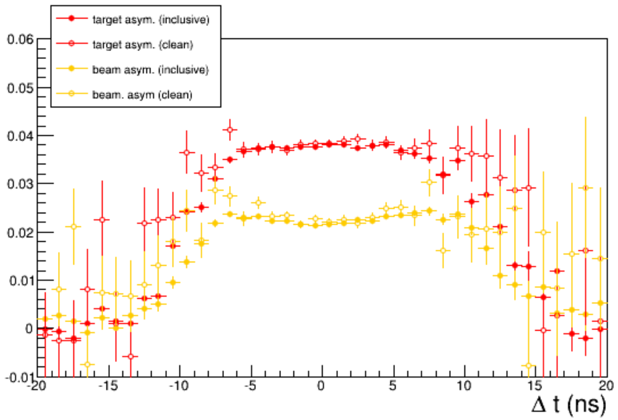
Atomic hydrogen target polarization $P = 96\%$

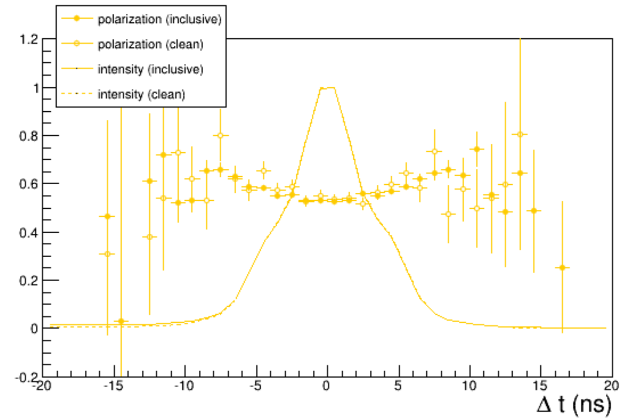
Molecular component $R_{H_2} = 3\%$ (by mass)

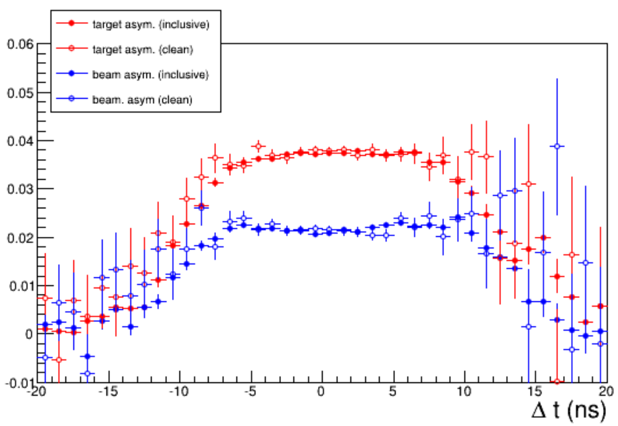
Global uncertainty from target polarization not included

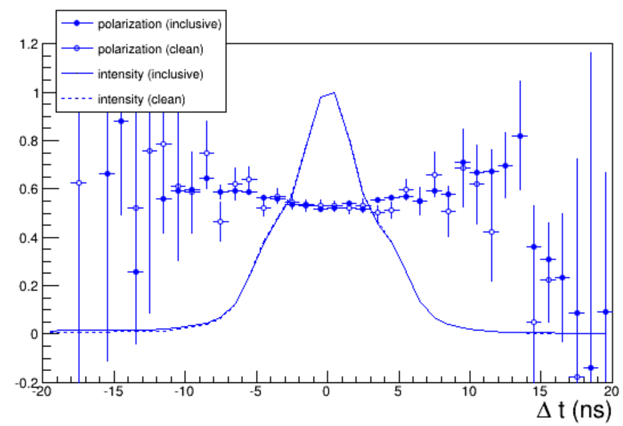
$-t$-range can be extended with punch-through protons

Longitudinal Bunch Profile

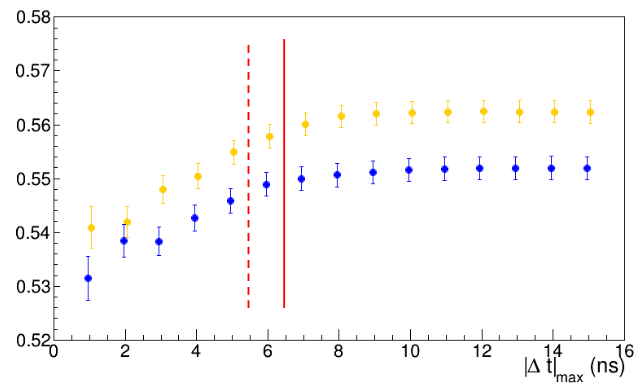








- Small differences between inclusive and clean asymmetries
- Consistent beam polarization measurement
- Longitudinal polarization profile (target asymmetry flat)
- Include longitudinal profile in luminosity weighting



$$1.5 < T_R < 7.0 \text{ MeV}$$

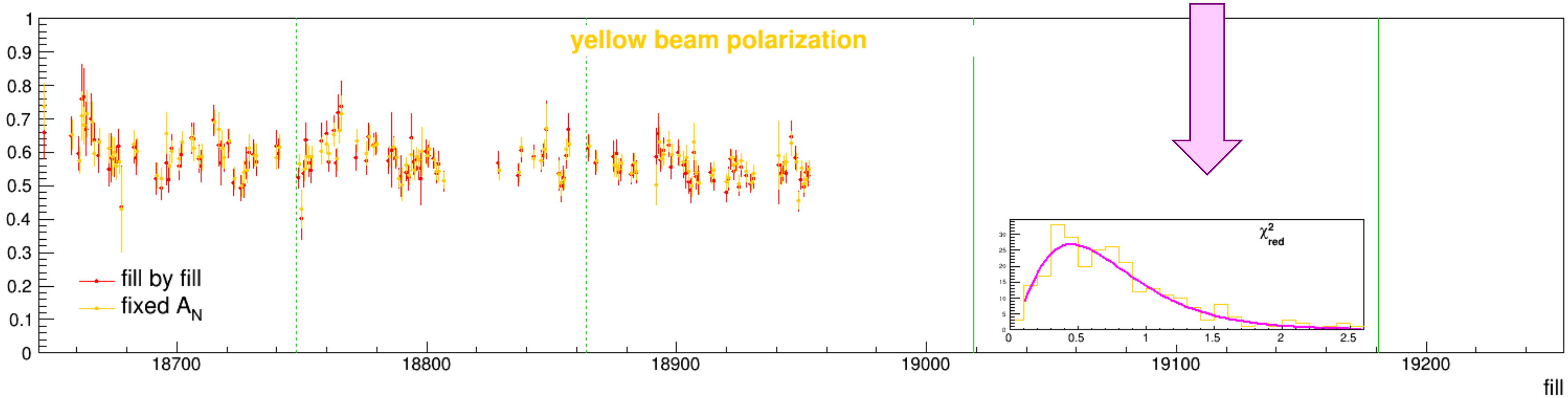
$$|\Delta t| < 6.0 \text{ ns}$$

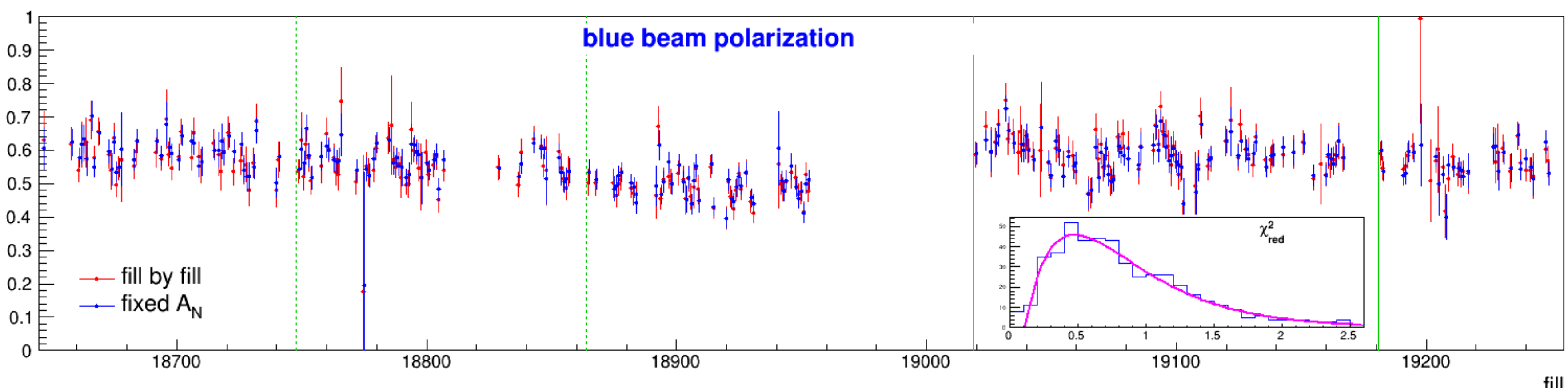
$$|\Delta m_{miss}| < 60 \text{ MeV/c}^2$$

Final Beam Polarizations 2015

Atomic hydrogen target polarization 96%
H_2 content 3% (mass)

Ratio of target/beam asymmetries
$1 < E_{recoil} < 7$ MeV (six bins)
Fit to constant



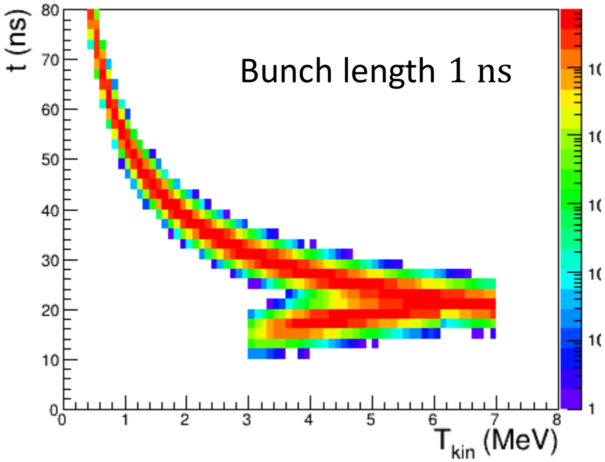


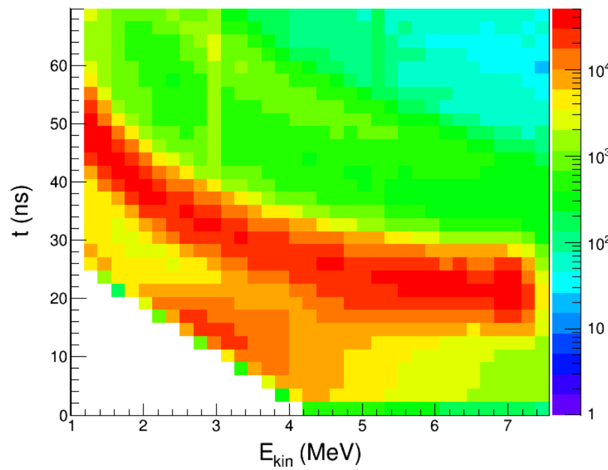
use fixed A_N for $p + p$

use fill by fill ratio for $p + A$

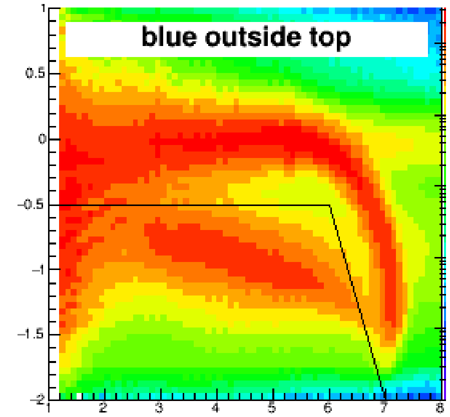
Elastic Recoil & Inelastic Background

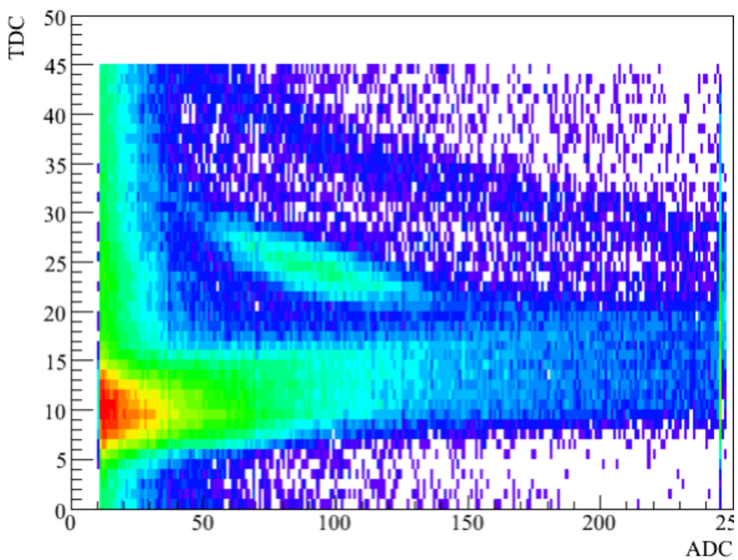
toy simulation





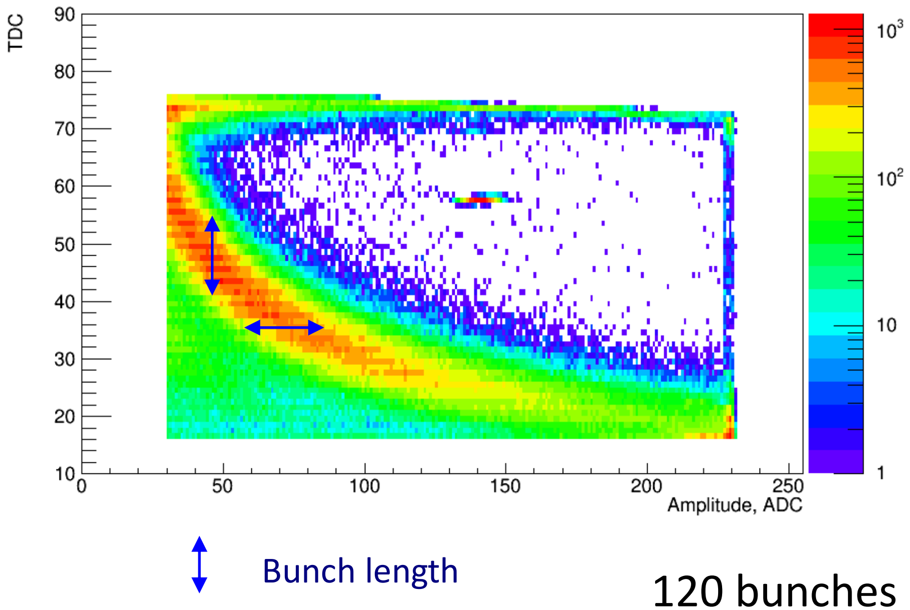
waveform rise

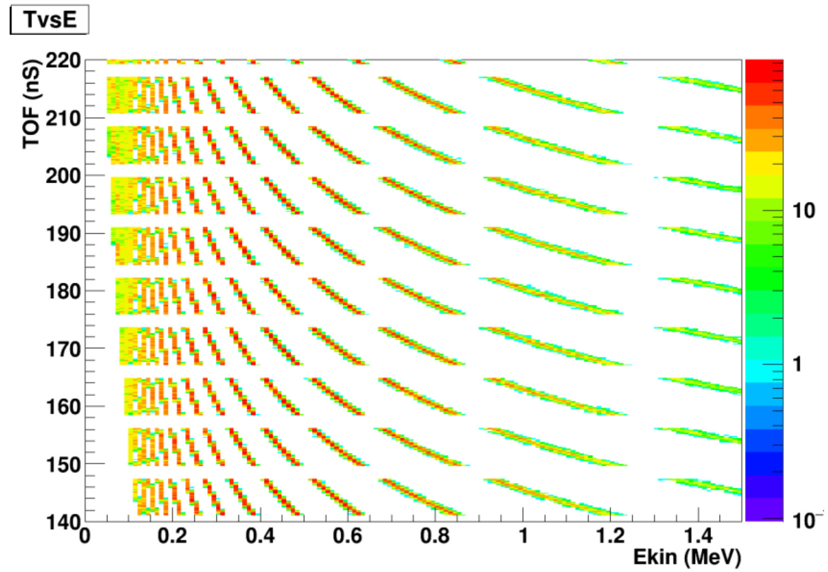




- Elastic $p + p \to p + p$ (HJET)
- DAQ rate $\approx kHz$
- Background rejection
  - Punch through recoil protons
  - *Slow* hadrons from hard QCD events

From RHIC to eRHIC





120 bunches → 1320 bunches

106 ns → 9.6 ns

- Carbon polarimeters (high rate)
- Reduced bunch spacing requires rejection and understanding of background
- Potential background asymmetry or dilution
- Loss of increased asymmetry at lower energies, $A_N(-t)$

Summary

- Polarimetry at RHIC
  - Combination of fast devices with absolute normalization
  - Essential input for experiments
  - Fast feedback during collider operation
- Be prepared for surprises
  - Transverse bunch polarization profile
  - Longitudinal bunch polarization profile
  - Direction of polarization vector
  - Systematic uncertainties
    - Molecular H_2 background
    - Inelastic background
    - Energy resolution, gain variations

BACK UP

Energy Calibration

Calibrations are done every few days:

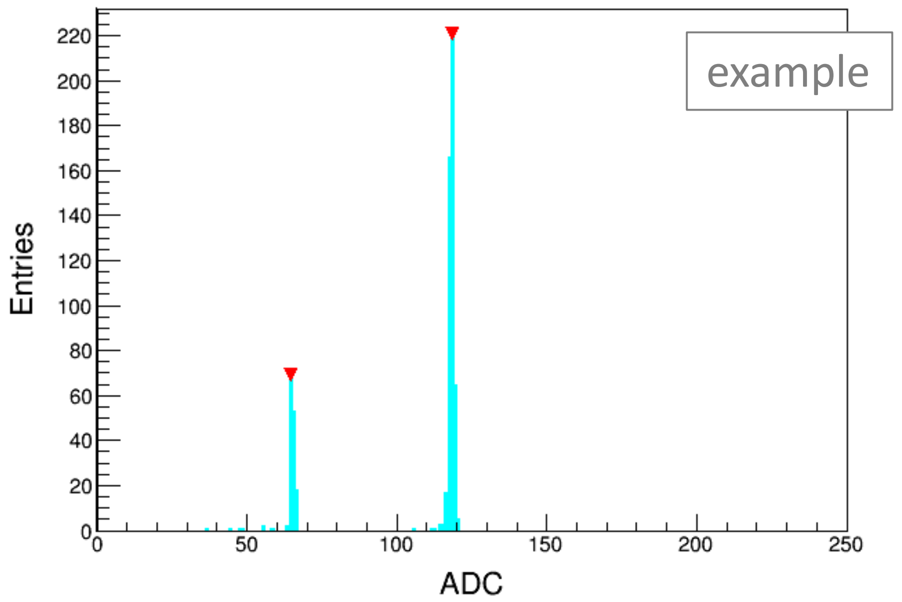
- Gain
- Entrance window (dead layer)

Two different α-sources

$$E_\alpha(Gd) = 3.183 \text{ MeV}$$

$$E_\alpha(Am) = 5.486 \text{ MeV}$$

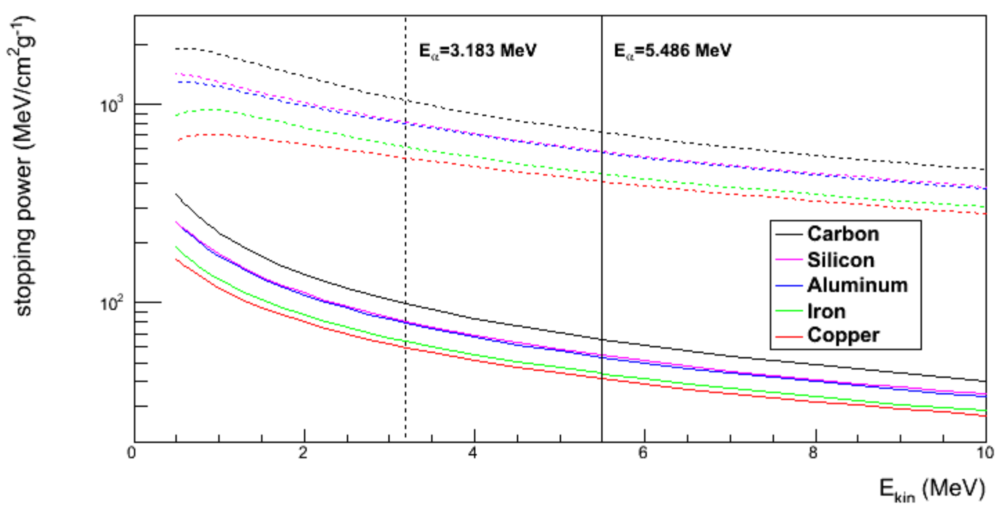
Resolution of peak finding is within 1 ADC count



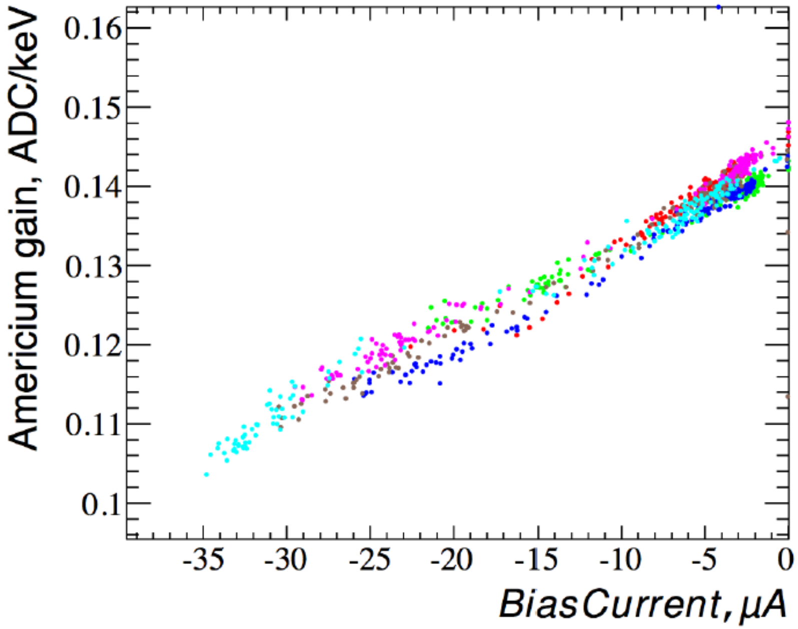
Stopping power for protons and α-particles from NIST database:

$$\Delta E_{\alpha(Am)} = 0.72 \cdot \Delta E_{\alpha(Gd)}$$

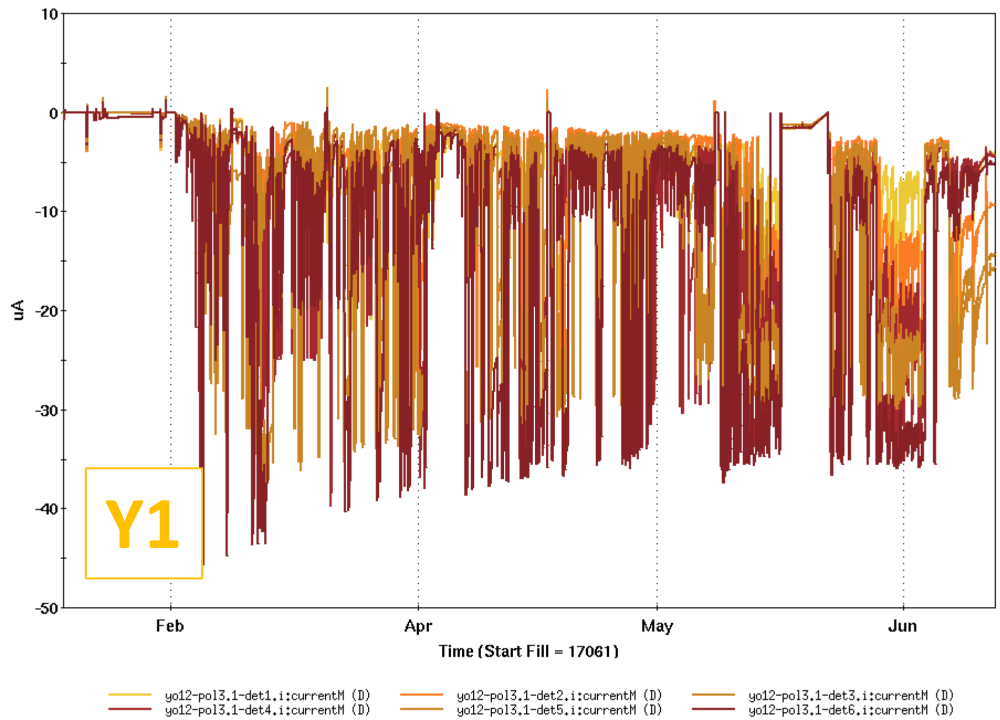
$$\Delta E_P = 0.44 \cdot \Delta E_{\alpha(Gd)} \cdot E[MeV]^{-0.64}$$



Gain Variations

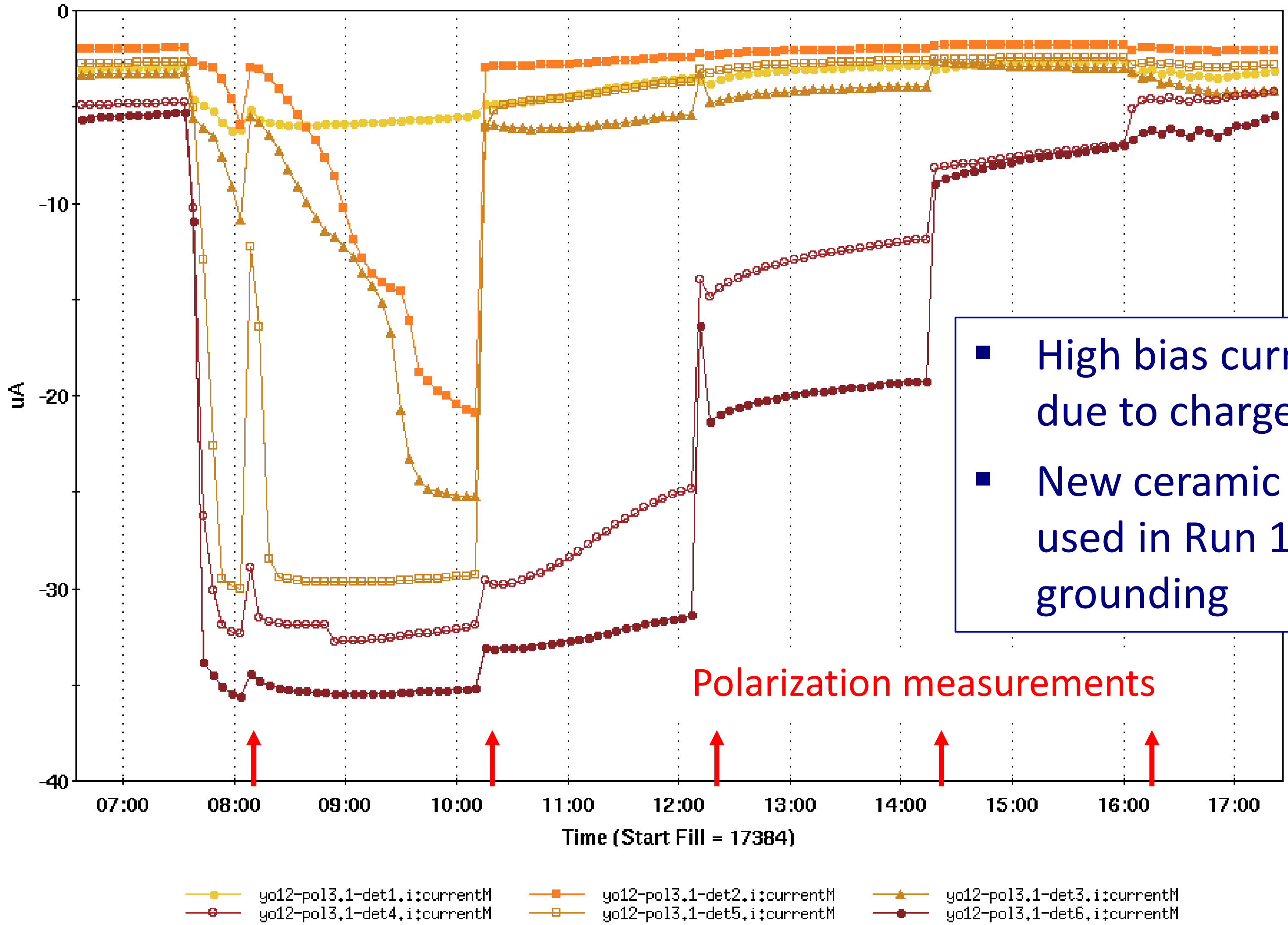


- α-calibrations typically done at the end of each fill
- Essential for identification of recoil Carbon



- Large variations observed between different calibrations
- Correlated with leakage bias current

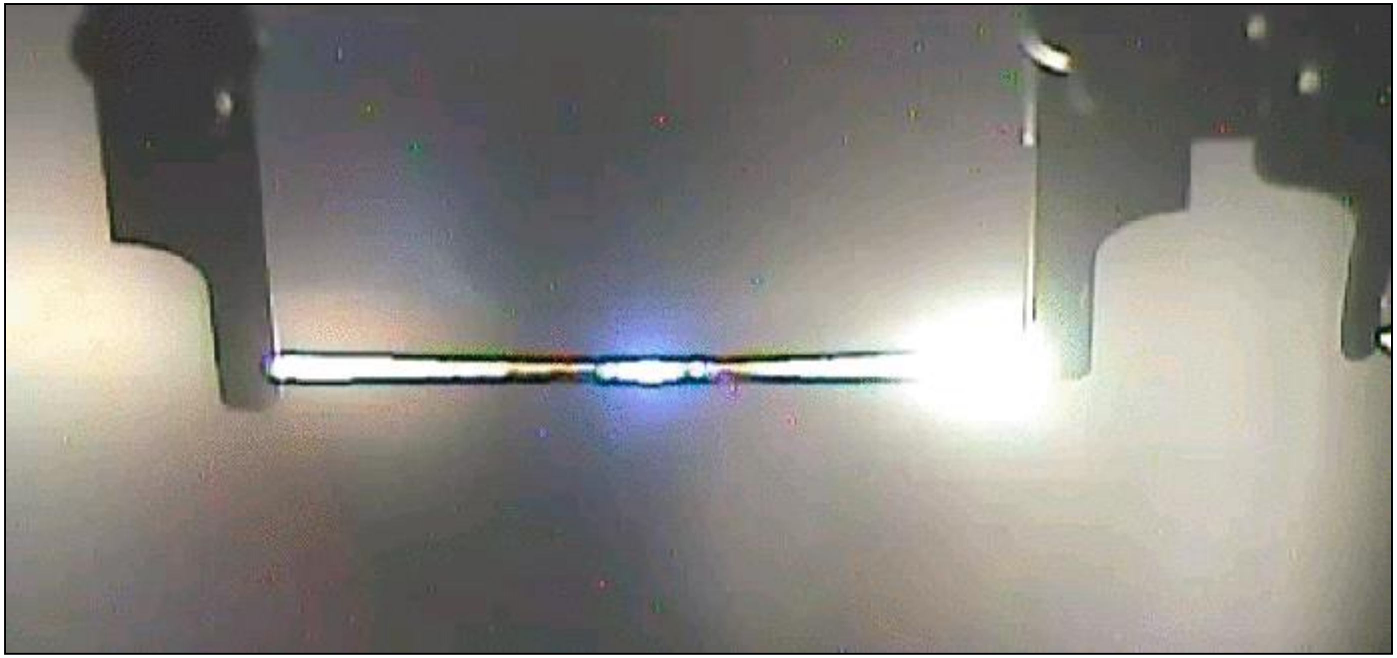
Leakage Bias Current (Example)



Polarization measurements

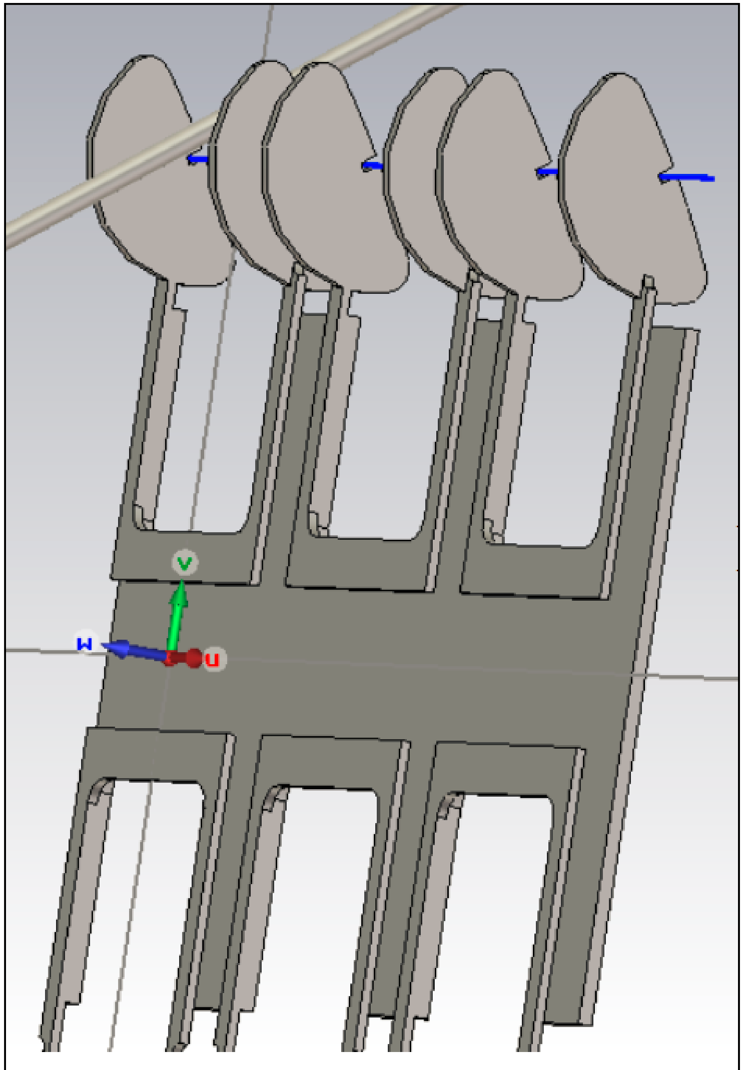
- High bias currents probably due to charge up
- New ceramic boards were used in Run 13 with different grounding

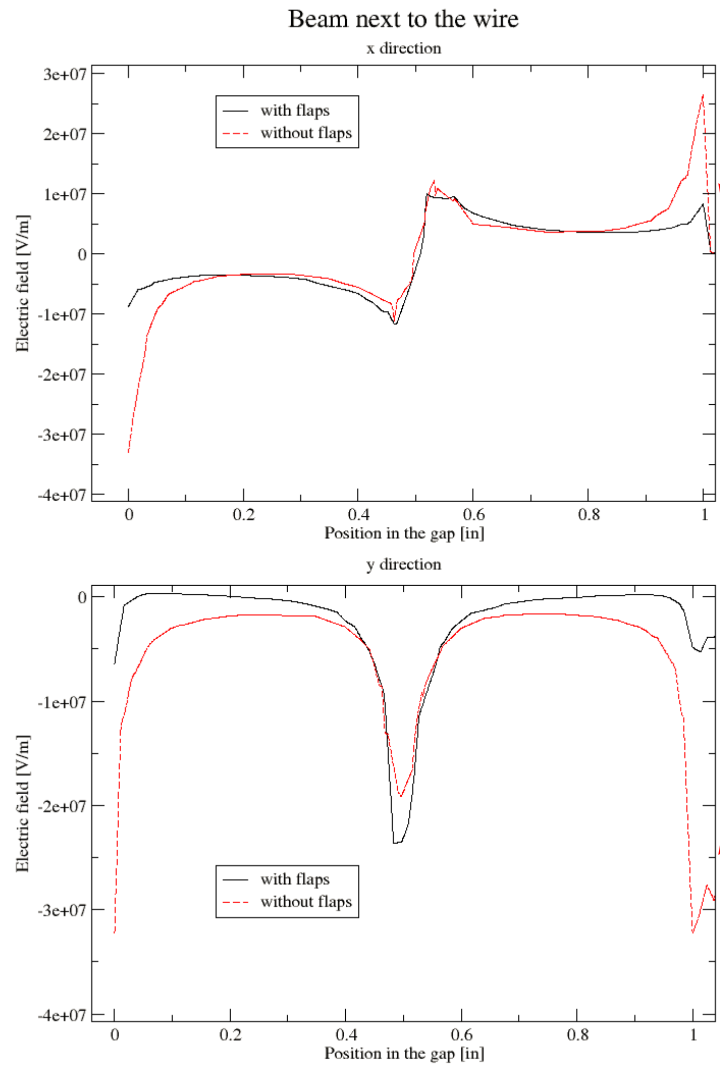
Target Lifetime



- Target tails start to glow when outside of beam
- Most targets break near the end
- Induced electron motion from high-frequency electromagnetic fields in the machine (200 MHz RF) → provide surface for the field lines to spread out

Electric Field at Target Location

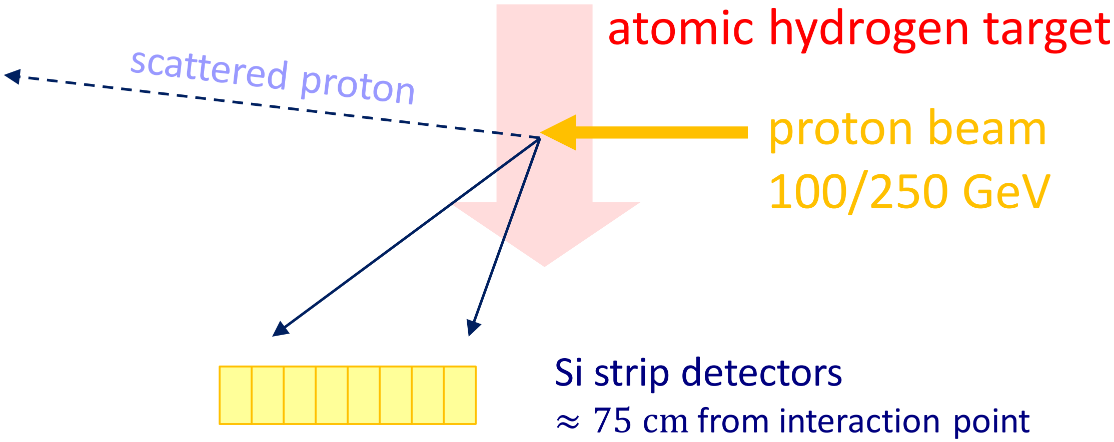


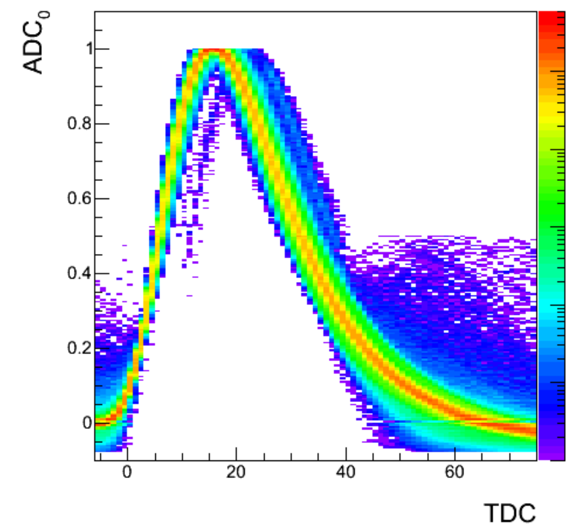


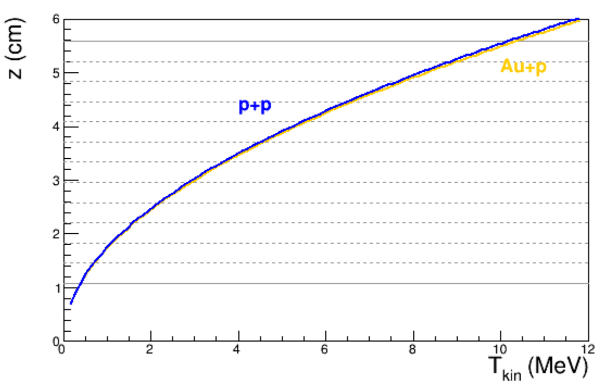
avoid spikes at the ends

simulation by J. Kewisch

Kinematics & Acceptance

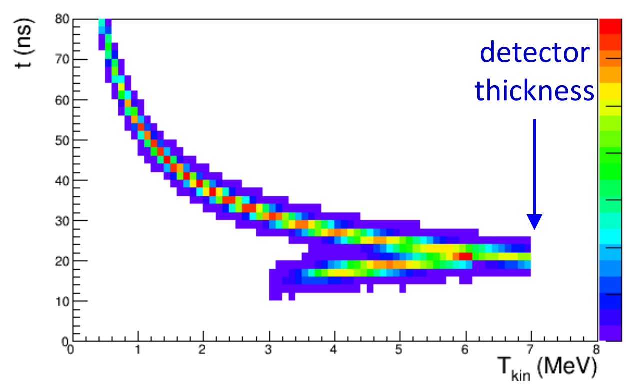






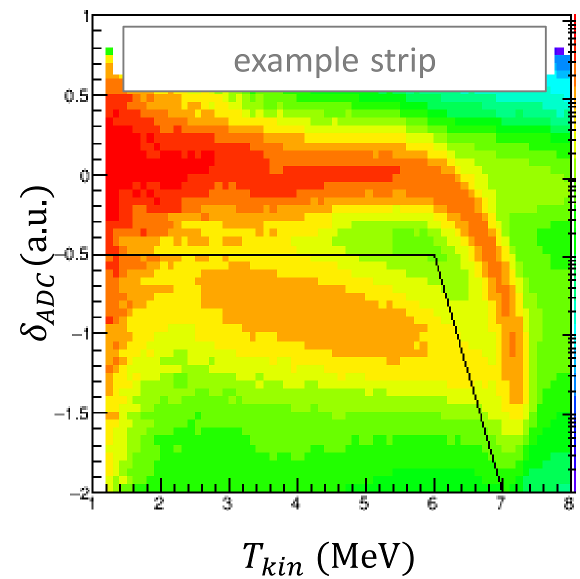
Toy simulation

non-relativistic: $T_{kin} = \frac{1}{2}mv^2$



target width: $\sigma_T = 0.3$ cm

bunch length: $\sigma_B = 1.0$ ns



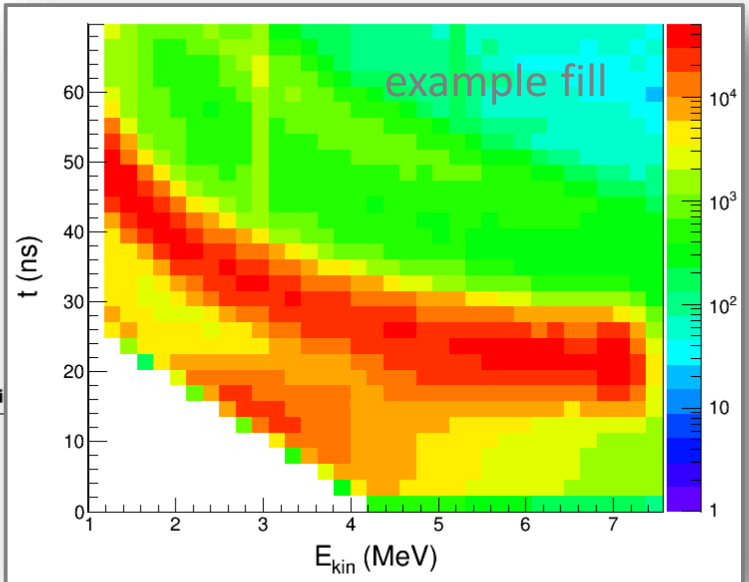
QA: Kinematics

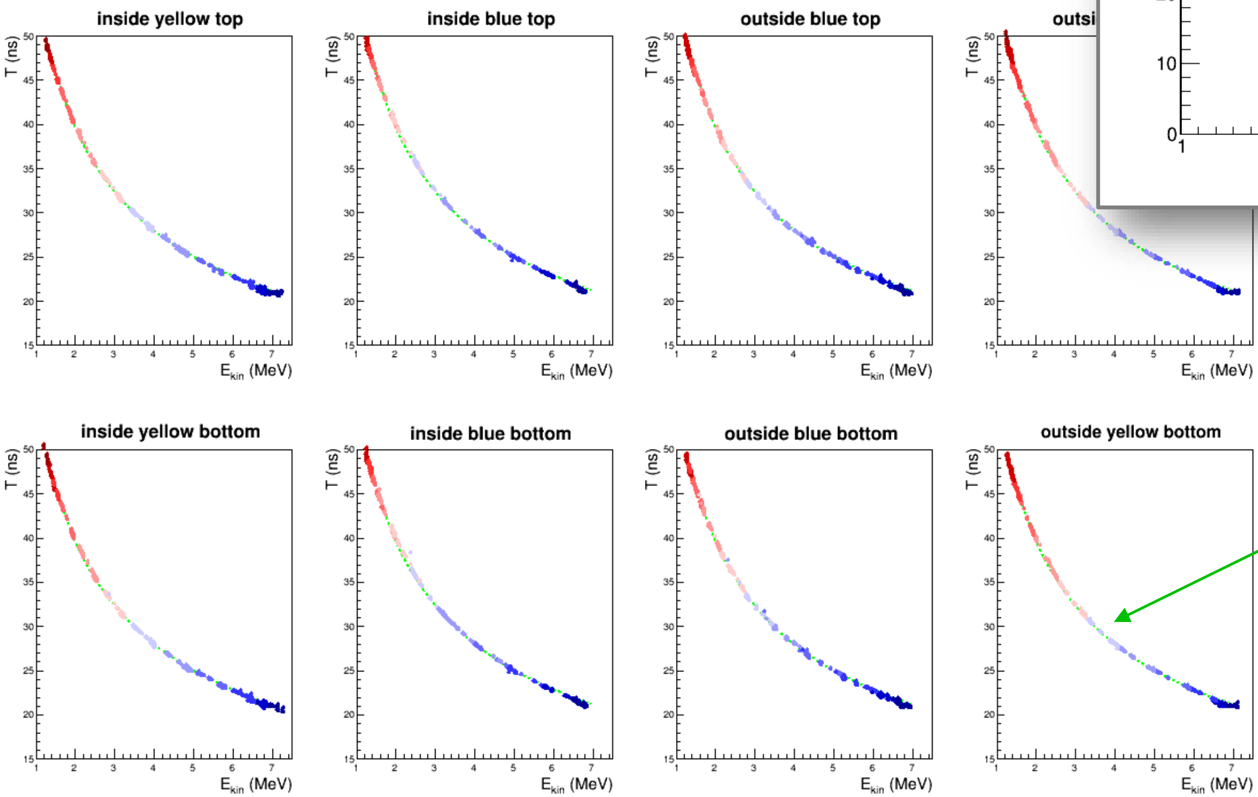
Elastic proton recoil selection:

After energy and T_0 calibration

$$\left|m_{miss} - m_p\right| < 100\ \mathrm{MeV}/c^2$$

$$|\Delta t| < 5\ \mathrm{ns}$$





Fit to ALL data, plotted under the distributions in each detector

Si-strips:
red – central to
blue – downstream

Detector Alignment

Magnetic holding field for target polarization changes acceptance of detectors on left and right sides

Outer correction field is adjusted for compensation

For missing proton mass:

$$\sin\theta = \frac{p'}{2\cdot m_p \cdot p_B}(2\cdot E + 2\cdot m_p - T_R)$$

Missing mass:

$$M_{miss}^2 = \begin{pmatrix} E + m_p - E' \\ p_B - p' \end{pmatrix}^2$$

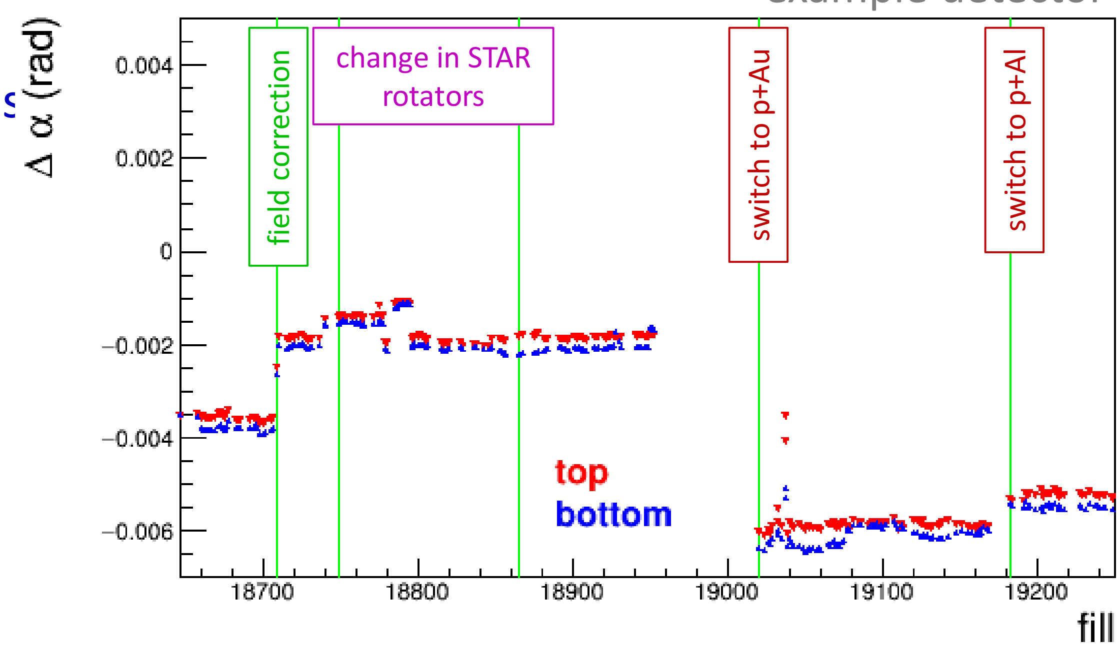
Non-relativistic recoil:

$$p' = \sqrt{2m_p T_R}$$

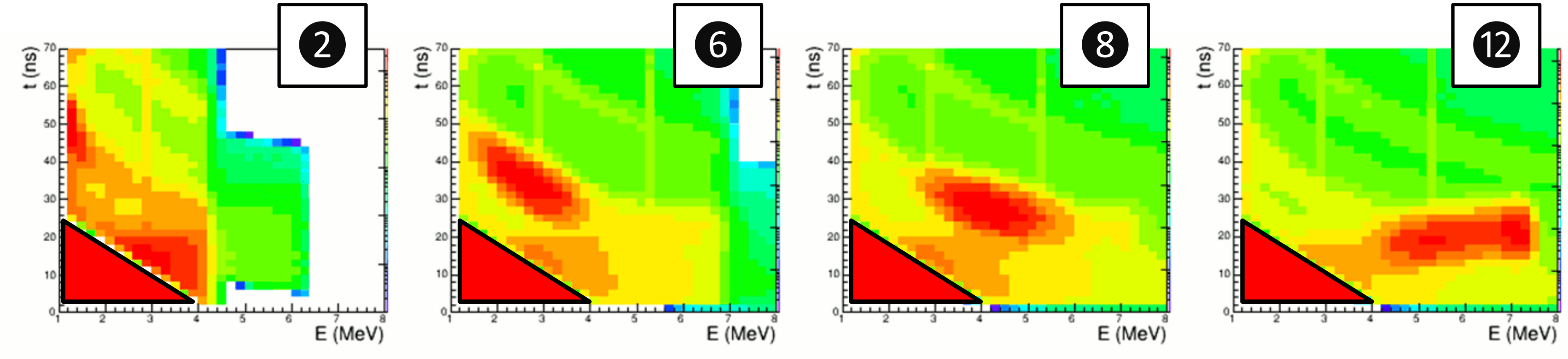
Compare with geometry of detector (averaged over 12 strips)

p+Au and p+Al operation had a significant beam angle on the jet target

example detector



Kinematics

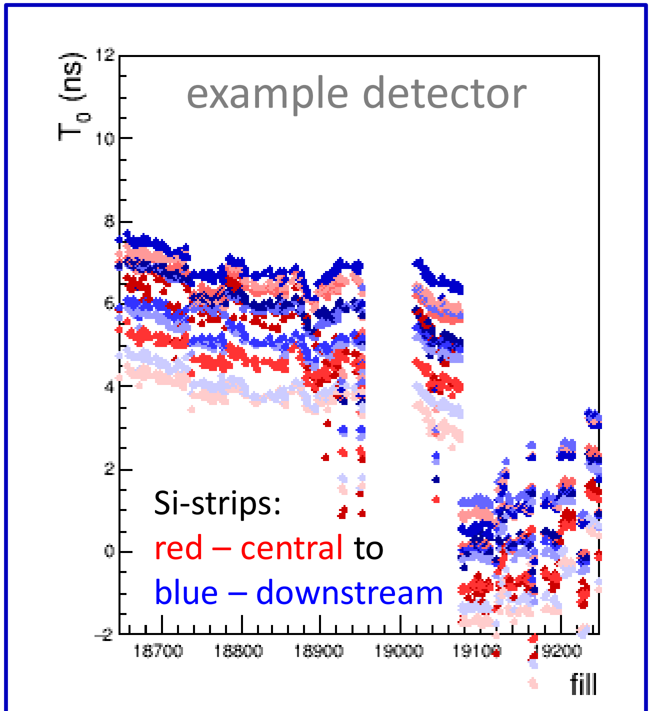


12 strips per detector

Removed peak in prompt hits at low ADC/TDC region

Using elastic p-recoil signature for time-of-flight offset determination

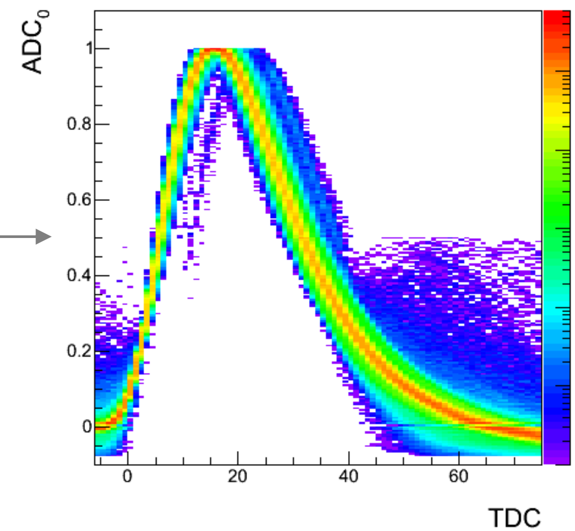
- Slow drift with time (detector/read-out)
- Big jumps when changing the DAQ system



Stopped Recoil Protons

Normalized to ADC_{max}

Slope δ_{ADC} calculated in six TDC bins around ½ ADC_{max}



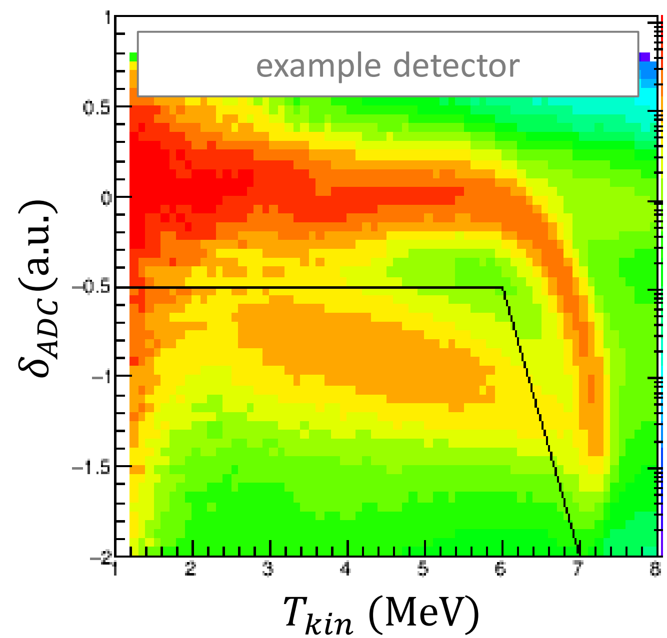
Slope of rise in waveform can be used to identify punch-through particles

Normalized waveform rise ($4.5 < E < 5.5$ MeV) in each detector

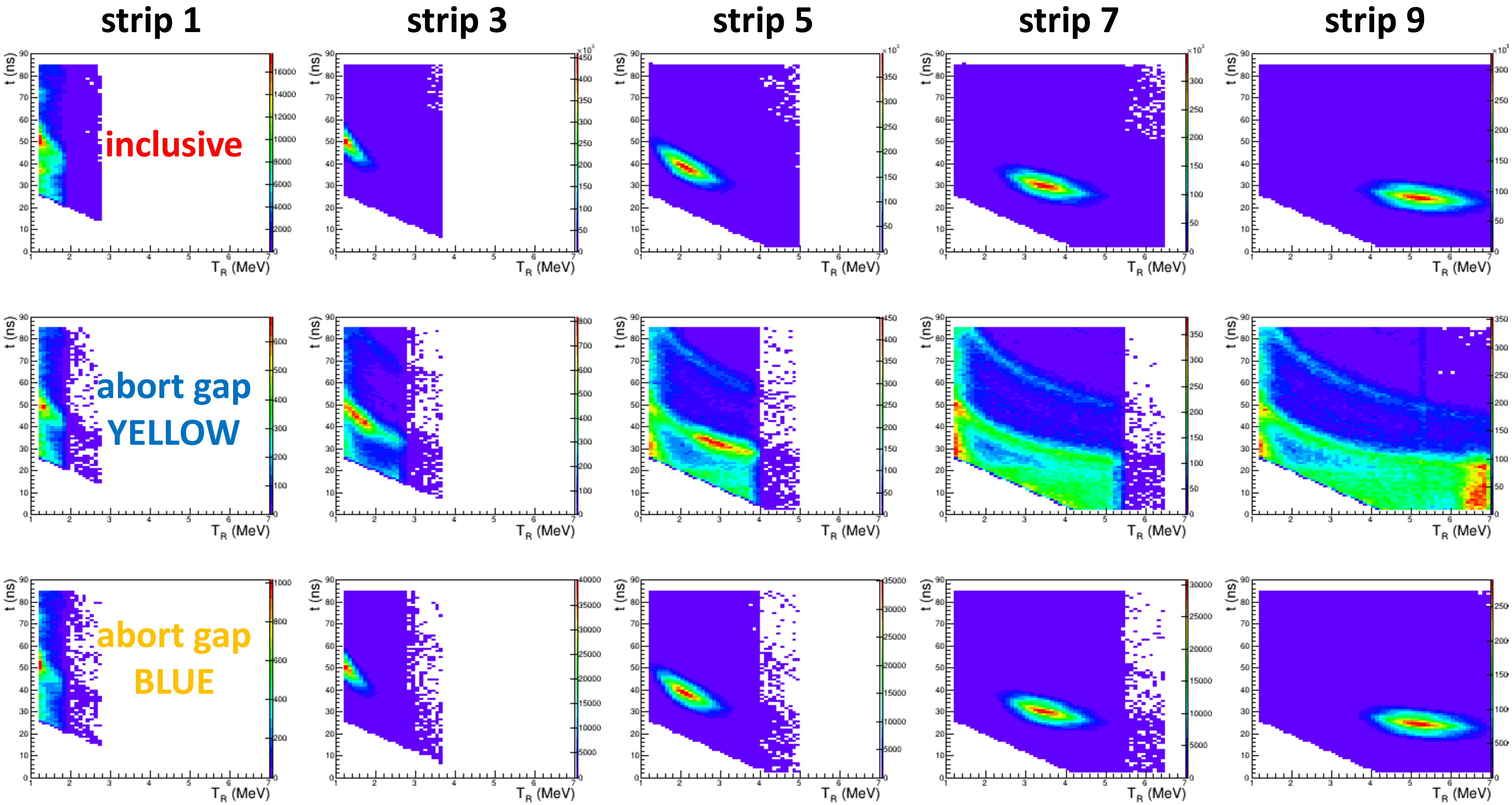
Independent of DAQ system (CAMAC/VME)

Remove punch-through particles:

$$(\delta_{\mathrm{ADC}} < -0.5) \wedge (\delta_{ADC} < 8.5 - 1.5 * T_{kin})$$



Kinematics & Detector Acceptance



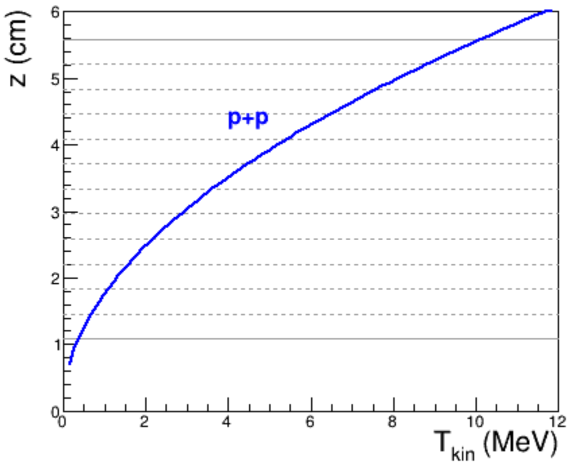
- significant contribution from opposite beam
- potentially with flipped target asymmetry

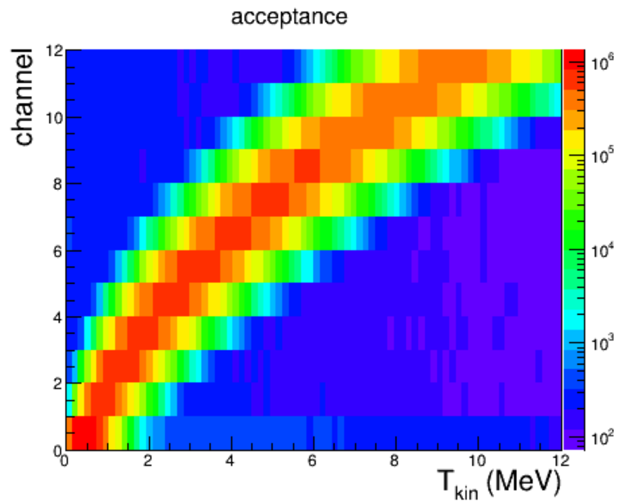
(*) not the same z-scales (linear)

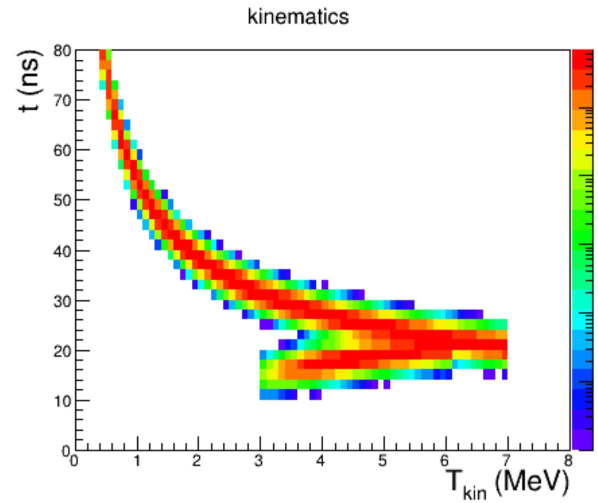
opposite beam fraction similar to previous slide

Target Size & Detector Acceptance

Toy model: atomic and molecular target size

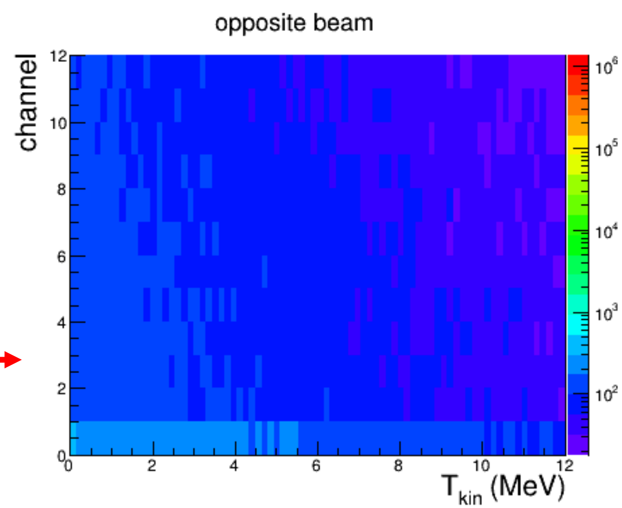


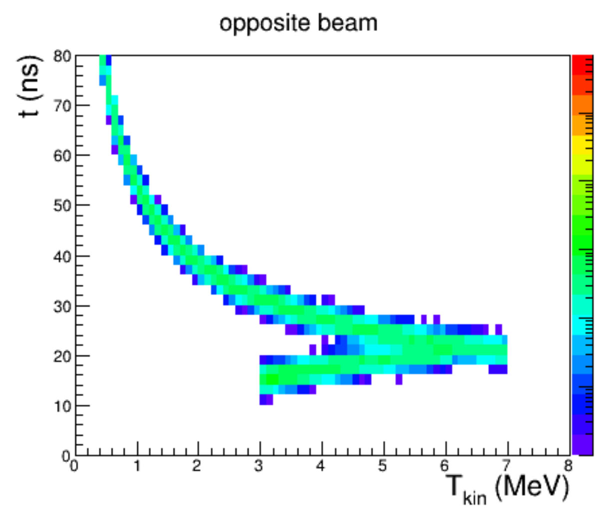




bunch length σ_B = 1.0 ns
target width σ_T = 0.3 cm
molecular width σ_M = 9.0 cm
molecular fraction r = 1%

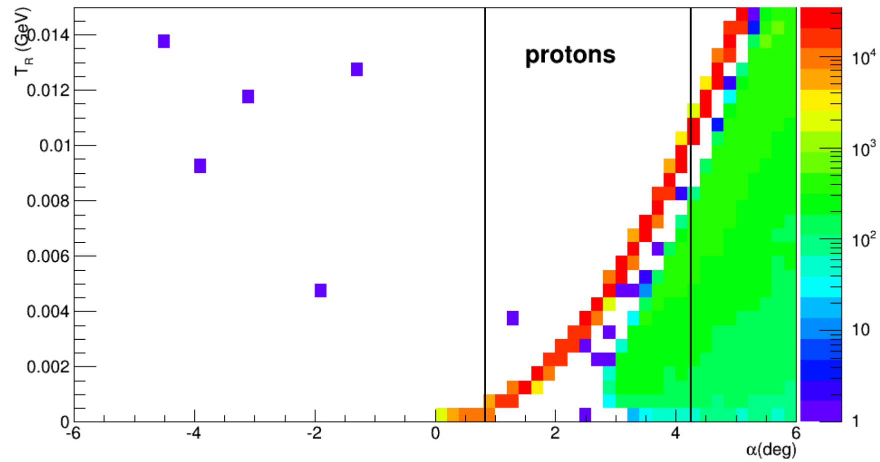
Completely elastic kinematics
Same vertical scale
$\approx 10^{-3}$ suppressed

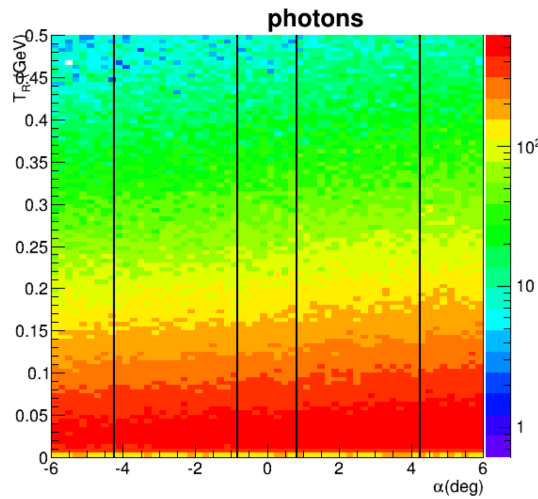


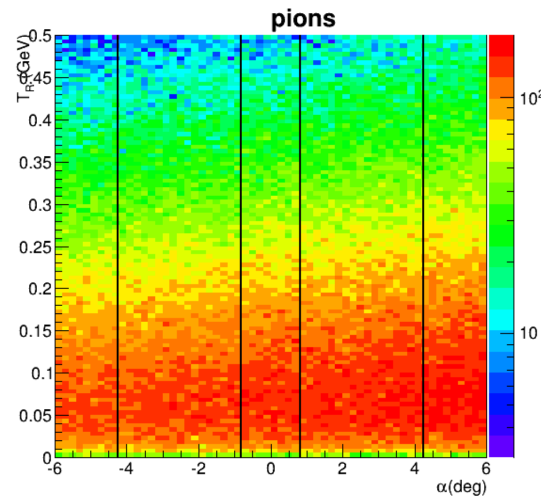


Prompt Background

- p+p at $\sqrt{s} = 21.6\ \mathrm{GeV}$
- PYTHIA 6.4.28, Perugia 0
  - QCD 2 → 2
  - Elastic
  - Diffractive
- Prompt background
  - pions / photons up to a few GeV
  - covering whole detector (down- & upstream)
  - target asymmetries suppressed from both beams





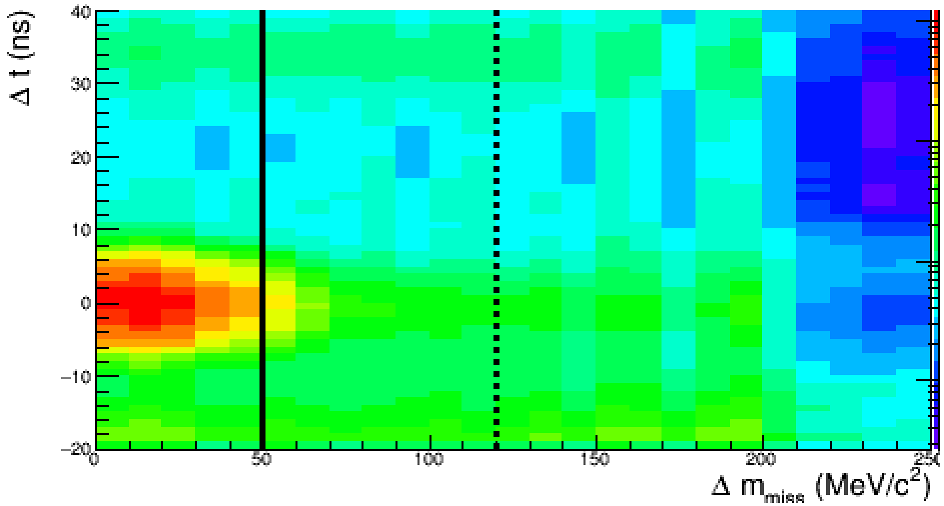


Signal & Background II

Δt: difference of measured time-of-flight to elastic signal, $t(T_R)$

Δm_{miss}: difference of missing mass to scattered proton (geometry after alignment correction)

Example (logarithmic z-scale)



Position of elastic proton signal is independent of energy and detector

Vertical stripes are a remnant of the spatial detector resolution

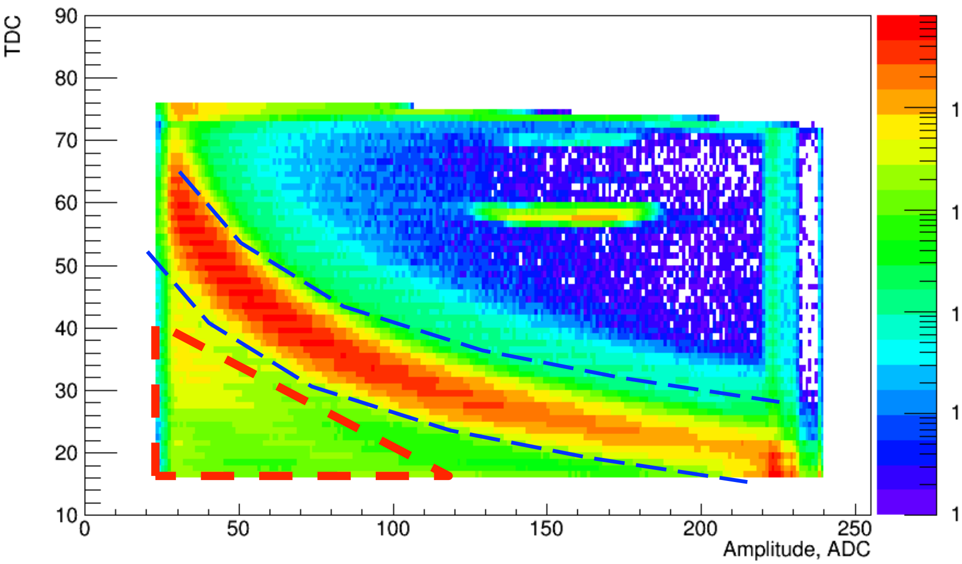
Punch through cuts are already applied

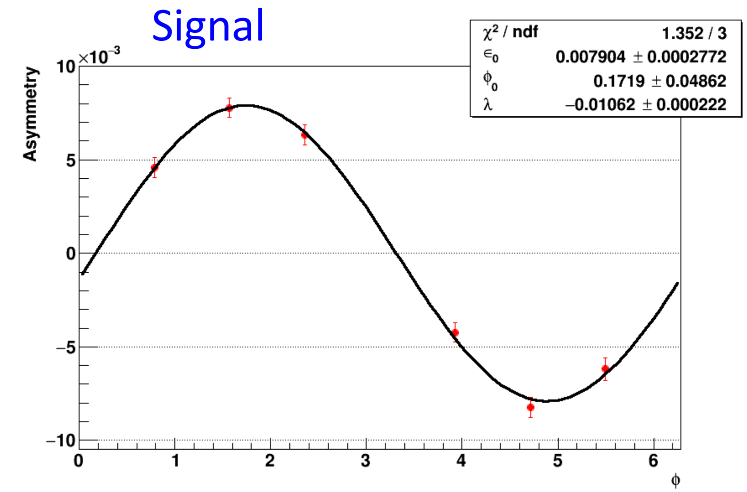
Define signal and background regions by missing mass

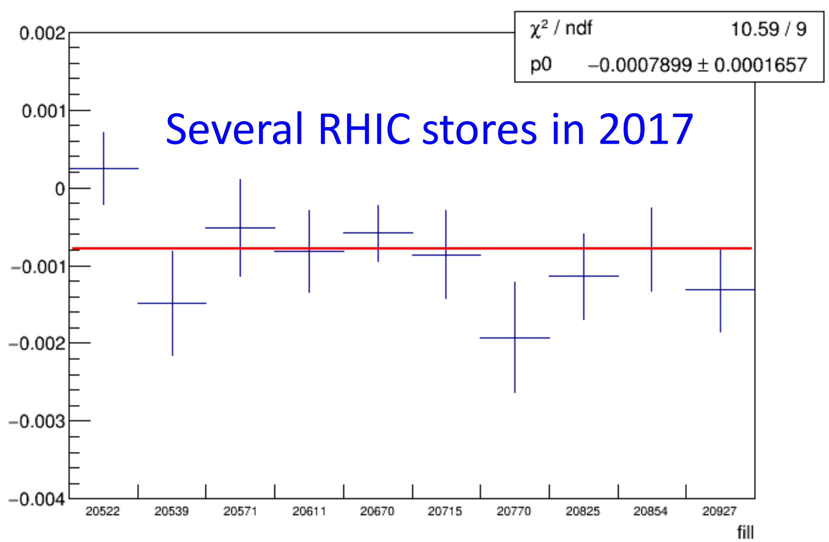
$$|m_{miss} - m_p| < 50\ \mathrm{MeV}/c^2$$

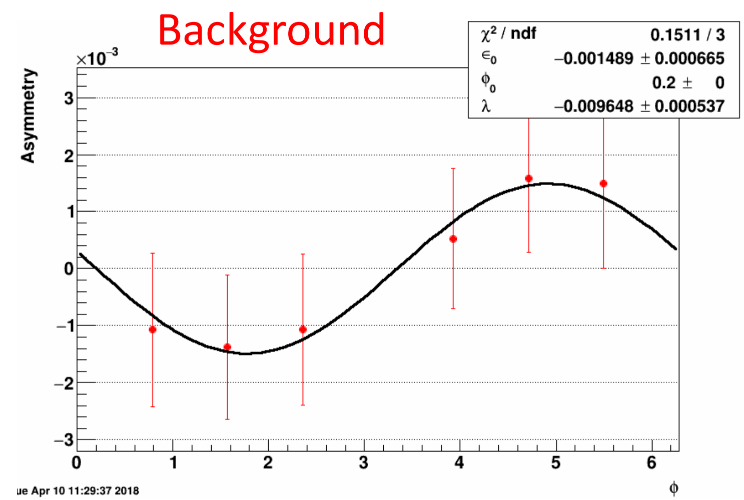
$$|m_{miss} - m_p| > 120\ \mathrm{MeV}/c^2$$

Background vs. Signal Asymmetry









Observed background asymmetry is a problem for polarization bunch pattern!